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THESIS

OPTIMIZATION OF A MARINE CORPS ARTILLERY BATTALION SUPPLY DISTRIBUTION NETWORK

by

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September 2007

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The supply distribution network consists of a set of locations connected by roads of known length. A small number of these nodes are logistics nodes that either supply or demand the commodities in our model, while the majority of the nodes are transshipment nodes. We use Dijkstra's algorithm to calculate the associated shortest travel distance between each pair of logistics nodes and then enumerate all possible tours through the logistics nodes. From this list of potential convoy routes, we determine the best combination of vehicles and supplies to assign to each in a manner that satisfies operational constraints and meets the mission objectives.

The decision the logistics officer has to make is to determine the convoy(s) that will deliver the demanded supplies in the shortest convoy route with the number of available vehicles to support the convoy. This model provides insight to the logistics officer about how to build convoys to distribute supplies optimally within the network.

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OPTIMIZATION OF A MARINE CORPS ARTILLERY BATTALION SUPPLY DISTRIBUTION NETWORK

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Submitted in partial fulfillment of the
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TABLE OF CONTENTS

LIST OF FIGURES

EXECUTIVE SUMMARY

Currently, the Marine Corps does not have a program or system to distribute supplies in support of combat operations in an optimal manner. We consider the problem of re-supplying a forward-deployed United States Marine Corps artillery battalion. Specifically, we model a supply distribution network of roads between the battalion supply area (BSA), the firing batteries, and the headquarters (HQ) battery. Our objective is to develop a decision support tool to help a logistics officer build efficient supply convoys that deliver all demanded supplies to the requesting units in the shortest travel distance.

The supply distribution network consists of a set of locations connected by roads of known length. There are two types of nodes in this network: logistics nodes (BSA, HQ, Alpha, Bravo, and Charlie) and transshipment nodes. Using Microsoft Excel with Visual Basic for Applications (VBA), we enumerate all combinations of convoys that travel to and from the logistics nodes. Thus, the enumeration only involves the logistics nodes and does not consider the transshipment nodes. The Dijkstra algorithm considers all nodes within the network and solves for shortest possible path between the logistics nodes. From the enumerated list of potential convoys, we determine the best combination of vehicles and supplies to assign to a convoy in a manner that satisfies operational constraints and meets the mission objectives. For the purpose of this thesis, we consider the following classes of supply:

- Class I - Subsistence which includes gratuitous health and welfare items and rations to include water;
- Class III - Petroleum, oil, and lubricants (POL); and
- Class V - Ammunition.

The logistics officer must determine the convoy(s) that will deliver the demanded supplies in an efficient manner.

Planning and executing these sustainment operations is a difficult task. The ability to provide logistical support in a constantly changing environment requires up-to-

date information on locations and demand requirements as well as constant coordination between the units. Our model and computational framework not only helps to find the shortest route from location to location, it also serves as a decision support tool that provides the logistics officer with solutions that maximize the available vehicle's load capacity while minimizing the convoy's total vehicle distance.

I. INTRODUCTION

A. PROBLEM

The United States Marine Corps (USMC) is constantly developing and revising its tactics, techniques, and procedures in order to enhance the effectiveness of its missions and the ability to sustain forward-deployed units. One significant challenge that arises when executing USMC operations is the logistics planning required to support and sustain forward deployed units. This thesis considers the USMC supply distribution network and addresses the question: how does one distribute sustainment supplies to the forward-deployed units in an optimal manner?

B. PURPOSE

The primary purpose of this thesis is to develop a decision support tool to plan and execute supply distribution in sustainment operations. We design this tool to use real-world, real-time information to optimize the supply distribution network. Specifically, with this tool, the logistics officer can incorporate the current locations and actions of his unit into decisions for optimally distributing the supplies required to sustain his unit as well as fill unanticipated critical demands and requests from the field.

C. BACKGROUND

Currently the Marine Corps does not possess a planning tool or system that distributes supplies in support of combat operations in an optimal manner. The author was previously assigned as a ground supply officer for 3d Battalion, 12th Marines, 3d Marine Division (an artillery battalion stationed on Okinawa, Japan) and in that capacity faced two critical challenges. The first challenge was to maintain the operational tempo. The second challenge was to calculate an optimal distribution plan for the daily sustainment supplies as well as to satisfy all rapid supply requests to the numerous positions occupied by the battalion’s firing batteries and headquarters element. There are currently no supply distribution programs or models that use network data to assist the

logistics officer in planning his supply distribution routes. To address this problem, this thesis uses data from a Marine Corps artillery battalion and from Marine Corps Doctrinal Publication 4 (*Logistics)*.

1. Description of a United States Marine Corps Artillery Battalion

A Marine Corps artillery battalion consists of a headquarters battery and three firing batteries comprised of six 155MM Howitzers each. The primary mission of the battalion is the direct support of the Marine Corps infantry regiment in time of conflict: either in the traditional fashion of artillery support to maneuver forces, or by providing batteries to serve as provisional rifle companies. The battalions are currently transitioning from the old M198 Howitzer whose maximum effective range is 30 kilometers and weighs 15,758 pounds to the new M777 which has a maximum effective range of 40 kilometers and is significantly lighter at 9,200lbs. Table of Organization (T/O) 1142G shows that the headquarters battery consists of 193 Marines, and T/O 1113G shows that each of the three firing batteries has 143 Marines, making the battalion total 634 Marines assigned to the command.

a. Command Element

The commander of the battalion is a Lieutenant Colonel who is assisted by the battalion command section. The battalion command section consists of the officers and staff non-commissioned officers of headquarters battery. The battalion commander is responsible for command and control as well as the direction and coordination of fire support.

b. Headquarters Battery

The mission for the headquarters battery is to provide the battalion commander with the means for effective command and control of the artillery battalion as well as administrative and logistical support for the headquarters battery, firing batteries, and attached units.

c. Firing Battery

The firing battery, an element of an artillery battalion, provides direct support, general support, reinforcing, and support reinforcing fires to support a Marine Air Ground Task Force (MAGTF) conducting combat operations. The weapons within the battery include six 155mm Howitzers, medium and heavy machine guns, grenade launchers, and individual weapons that comprise the firepower capabilities of the battery. Within the battery there is the fire direction center (FDC). The FDC and battery operations center provide technical and limited tactical fire direction for the firing battery. The batteries are required to maintain automated and manual technical fire direction capabilities.

D. OBJECTIVES

The objective of this thesis is to develop a tool to support logisticians in their efforts to make well-informed decisions in determining supply routes and types of convoy to deploy when supporting mission requirements.

E. RELATED WORK

There has been considerable work on problems related to networks and convoy building. More specifically, the vehicle routing problem (VRP) (e.g., Toth and Vigo, 2001) is a problem that was defined more than 40 years ago. The problem involves determining a set of routes that are optimal for vehicles and convoys (fleets) to deliver items to a collection of customers. The traveling salesman problem (TSP) (e.g., Lawler et al., 1985) is also relevant to this thesis with respect to determining the shortest route/distance one has to travel in order to visit as many customers as possible. The previous thesis work of Captain Matthew D. Bain of the United States Marine Corps addresses the challenge of supporting a distributed operations (DO) platoon with critical logistical requirements (Bain 2005). Bain’s thesis specifically addresses the tradeoff between logistical effectiveness and response time. However, his thesis does not address issues related to convoy building and routing of convoys over a supply area.

F. THESIS FORMAT

Chapter II outlines the role of the logistics officer and details the classes of supply, time requirements and battle tempo, priority of efforts, and vehicle support. Other factors not explicitly addressed in this study are the inherent risks of supply routes, the urgency of supplying the units, and the movement of the battalion. Chapter III presents the model formulation, including Dijkstra's algorithm, variable descriptions, Excel spreadsheets with the General Algebra Modeling System (GAMS) interface, and the description of supply distribution networks that are used. Chapter IV describes two operational scenarios and presents the results obtained from our model and decision support tool. Chapter V summarizes our conclusions and provides recommendations for follow-on research.

II. ROLE OF THE LOGISTICS OFFICER

A. FACTORS OF CONSIDERATION

The Marine Corps has identified logistics as an integral part of warfighting. The role of logistics is to provide assistance to the commander in making the best use of the resources available to him to accomplish the mission. These resources must sustain the unit's combat power throughout the course of operations. The task of the Logistics Officer is to ensure that the Marines on the fighting line have the gear and sustainment supplies they need to deliver the maximum amount of combat effectiveness to the enemy. In short, the challenge of logistics is to make sure that everything is at the right place at the right time.

Logistics is regarded as both a science and an art, and the logistician must be familiar with both as described in the Marine Corps Doctrinal Publication 4, *Logistics* (MCDP 4). The *science* of logistics requires the logistics officer to understand his mission requirements and apply appropriate models, with corresponding formulas, calculations, tables, and rules of thumb, to support properly the commander's intent. The *art* of logistics requires the logistics officer to use the information obtained from the scientific methods and apply those results with experience, intuition, creativity, and sound judgment. When the two are put together, the Logistics Officer can develop feasible solutions to complex logistics problems.

The Logistics Officer must follow the *Logistics Process* as defined in the Marine Corps Doctrinal Publication 4 (MCDP 4). This process involves the acquisition, distribution, sustainment, and disposition of resources. For the purpose of this thesis, we focus on the distribution step of the *Logistics Process*. The distribution step is complex. The logistics officer must manage the supplies moving in and out of the supply area and know the locations of the units he is supporting. He then has to forecast their demands and plan for the distribution of the supplies requested and required to sustain the units at their locations. This distribution task becomes very difficult when a unit moves to an obscure area with limited access. Other factors of the logistics process include the

location of warehouses, supply caches, vehicle assets, and the urgency of need assigned to the resource. The missing component within the distribution step of the *Logistics Process* is the decision about how to distribute the resources to the various positions and units within the operational area in an optimal manner.

Overall, the Logistics Officer is also responsible for six functional areas: supply, maintenance, transportation, general engineering, health services, and other services. As stated earlier, the focus of this thesis is the distribution of sustainment supplies. To understand better the scenario and apply the model to the logistics distribution problem, we must first consider a few critical factors that influence the decision of the logistics officer. They include: the classes of supply, the time and tempo of battle, and the vehicles available to support the logistics officer's distribution plan.

1. Classification of Supply

The Marine Corps has ten classes of supply. The classes and definitions as described from the Marine Corps Warfighting Publication 4-1 are given below.

I. Subsistence which includes gratuitous health and welfare items and rations

II. Clothing, individual equipment, tentage, and organizational tool sets

III. Petroleum, oil, and lubricants (POL)

IV. Construction materials, all fortifications, barrier, and bridging materials

V. Ammunition of all types

VI. Personal demand items or nonmilitary sales items

VII. Major end items

VIII. Medical/dental material

IX. Repair parts

X. Material to support nonmilitary programs

Individual supply items are assigned to one of these categories based on their characteristics and purpose. The logistics officer must maintain proper stock levels of supply as well as ensure he has orders placed to have the material on hand when his Marines need them. This is a critical area that requires the utmost attention. This thesis will focus on the distribution of the three classes of supply: Class I (Food / Water), Class III (Fuel), and Class V (Ammunition).

2. Time/Tempo

Perhaps the most heavily constrained commodity is time. As the battle or engagement changes, the logistics officer must be flexible and have the ability to plan, evaluate, then execute in a rapidly changing wartime environment. The Marine Corps has developed a process called the Planning, Decision, Execution, and Assessment cycle, or PDE&A (MCWP 4-1). By following this decision process, the logistics officer can be adaptable and flexible to meet the challenges of war as well as provide the commander with the best possible support. This thesis is intended to assist in the PDE&A cycle by developing a model and tool for identifying optimal distribution routes.

The other aspect closely related to time is tempo. The ability to maintain an operational rhythm with little to no interruption is essential. To ensure that operational tempo is maintained, the logistics officer must properly forecast and anticipate what, where, and when support is needed, as well as balance this support of resources with the other activities taking place within the area of operations.

3. Phases of Battle

Another important factor related to time and tempo that one must consider is the changing needs of the unit during the different phases of battle. The four phases are: the pre-attack phase, movement phase, attack phase, and defense phase, and they are typically experienced in this order. The pre-attack phase is the build up of resources and the establishment of the logistics capabilities and support pipelines. The second phase, movement, involves the unit relocating near the objective and ultimately enemy contact. The logistics officer must remain flexible and stay within reach of his unit so that he can

deliver whatever support and/or resources are required to sustain combat effectiveness. The next phase is attack: the battalion makes enemy contact and the unit tries to inflict maximum combat power to achieve objectives. At this phase, the priority of support shifts. The unit is now involved in a fire fight with the enemy and the need for fuel and water is replaced with a need for ammunition. The final phase is the defense phase. After defeating the enemy or driving him from the area, the unit establishes a perimeter defense and begins to assess damages and support requirements. The logistics officer must be ready to provide all capabilities and resources to get the unit back into fighting condition. The logistics officer must know what his role is in each phase of battle and be ready to provide support and resources to transition smoothly between them.

4. Priority

The commander determines who receives the priority of support based on the tasks assigned to specific units and the mission at hand. Also, at the commander's discretion, the priority of support may be based upon a particular piece of gear, a type of service support, or a given bulk quantity such as rations or fuel that are more critical to a specific unit. The top priority assigned by the commander is most often given to the unit or units in close contact with the enemy and/or have limited transportation capabilities. The logistics officer must be able to incorporate the priorities of his commander and be flexible in the face of changing priorities.

5. Vehicle Support

The logistics officer has a limited number of vehicles to support the units in the command. Thus, the transportation and distribution system must be highly adaptable to utilize efficiently this limited capability.

6. Time Horizon

The procurement, distribution, and consumption of supplies occur in different time scales, and the logistics officer must be familiar with all of them. Procuring supply commodities with long lead times requires a different level of attention than the shipment

of today's food and water. In considering the distribution component of the *Logistics Process*, we focus on the challenge associated with building a route and supply convoy in the immediate future.

7. A Changing Environment

Within the area of operations there is an established supply area or support services tent where vehicles and resources are collocated. From this location the logistics officer can track the locations of his unit that will require support as well as maintain visibility of his support assets. However, as time passes and the situation on the battlefield changes, the units often spread further apart making it difficult to coordinate supply routes. There is a need for a tool to calculate supply routes given the units location, the type of support needed, and to build a convoy that maximizes the efficiency of the vehicles on hand. This tool needs to incorporate real-time data and should obtain a solution quickly. Thus, as the operational environment changes, the logistics officer can rapidly adjust or replace the current distribution plans. Such a tool would help maintain the operational tempo and maximize the unit's combat effectiveness.

B. CONSTRAINTS

Logistic resources are usually constrained by several factors. These factors include, but are not limited to, warehouse capabilities, limited quantities, limited transportation assets, long lead times, communication breakdown, and a large maneuver area. These constraints must be dealt with individually and properly calculated in order to create a support plan that supplements the commander's intent and employment of his unit without any delays or operational pauses. There are, of course, more constraints than the handful mentioned, and with each mission there are new constraints specific to that operation.

The logistics officer must apply the *Logistics Process* and have detailed coordination with the units he supports to maximize the efficiency and effectiveness of the logistics operations. Developing a decision support tool that calculates the shortest convoy route within the supply distribution network will greatly assist the logistics officer in his mission planning.

III. MODEL FORMULATION

This chapter describes the key components of our model and decision support tool used to solve the distribution phase of the logistics process. We consider a scenario involving a forward-deployed United States Marine Corps artillery battalion. Specifically, we model a supply distribution network of roads between the battalion supply area (BSA), the firing batteries, and the headquarters (HQ) battery. Our objective is to develop a decision support tool for the logistics officer to build efficient supply convoys that deliver all demanded supplies to the requesting units in the least amount of time or distance.

A. SUPPLY DISTRIBUTION NETWORK

A network is a graphical representation of a system using nodes and arcs enhanced with additional data such as costs, capacities, supply, and demand. In this thesis, geographic locations are nodes and roads are the arcs connecting them. Nodes can be points of supply or demand, or they can be transshipment nodes (locations where two or more roads intersect). In this model, demand nodes correspond to the HQ battery and the firing batteries, and there is a single supply node corresponding to the BSA. The roads in the network are used as routes between two or more nodes. Our network terminology follows that of Ahuja et al. (1993, Ch. II)

1. Nodes

The supply distribution network has three types of nodes. There are the supply nodes (only one supply node for this problem), demand nodes, and transshipment nodes. The supply node is where each convoy begins and ends its distribution route which is assumed to be the location of the BSA. The demand nodes correspond to the locations of supported units. Transshipment nodes are typically intersections of roadways. For this problem the batteries will have a demand for three types of supply:

- I (Food / Water);
- III (Fuel); and
- V (Ammunition).

A demand node is labeled as such if there is a supported unit located there. The unit receives supply support if they have a demand for any amount of the three supplies. The model then determines the convoy route and order of delivery by the various inputs and constraints. A demand node could be visited even if there is no demand if the algorithm determines the route to be the shortest by passing through that node.

2. Arcs

Arcs connect nodes within the network, and in this context they correspond to roads. The arcs in the network are undirected, thus allowing two-way traffic to travel the roads. The model assumes the roads are easily traveled, and thus the arcs are not restricted on the type of vehicle traveling, the size of vehicle, or the weight capacity of supplies being distributed.

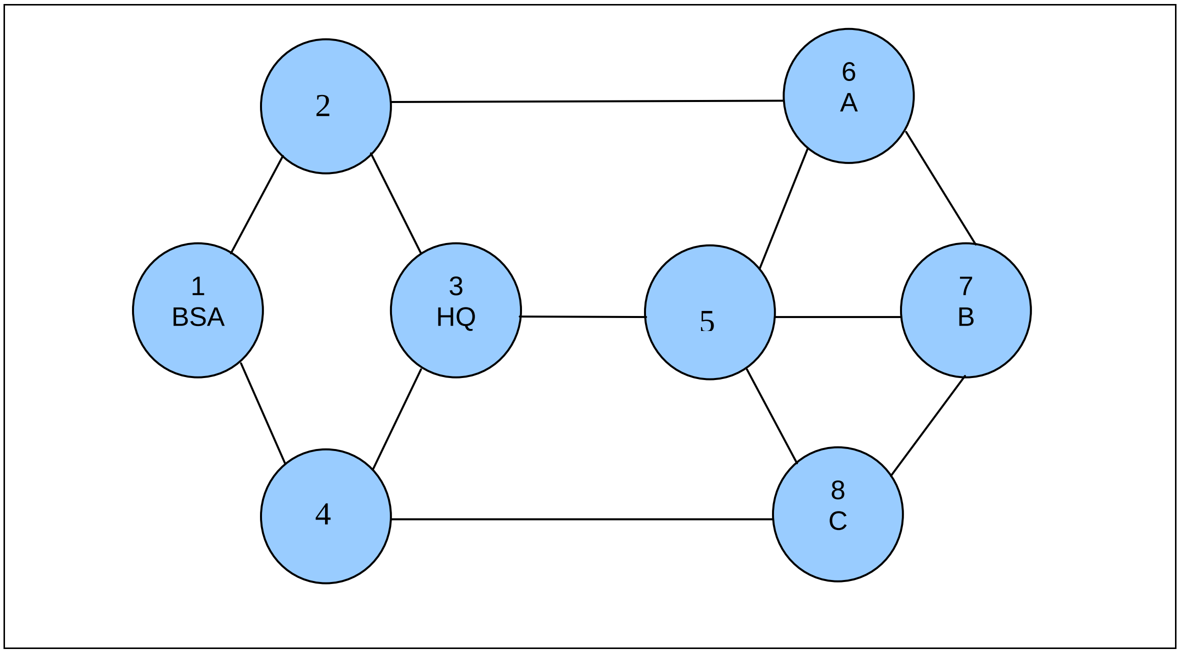


Figure 1. A simplified example of an artillery battalion and the node locations of the Firing Batteries (A, B, C) and HQ Battery. The arcs between the nodes represent the roads available to the logistics officer in planning the convoys around to distribute the demanded supplies.

B. MODEL INPUT

Inputs to the model include:

- The supply distribution network;
- Arc (road) lengths;
- The classes of supply;
- The locations of the supply (BSA) and the demand (Firing Batteries and HQ Battery) nodes;
- Amount of supplies demanded by each battery;
- The number of vehicles available per convoy; and
- The vehicle capacities, both weight and cubic feet.

Our user interface is an Excel spreadsheet into which the logistics supply officer enters data about the road network, battery locations, number of available vehicles, and demand levels for each class of supply supported by Visual Basic for Applications (VBA), the Excel program then solves the supply distribution problem in two phases.

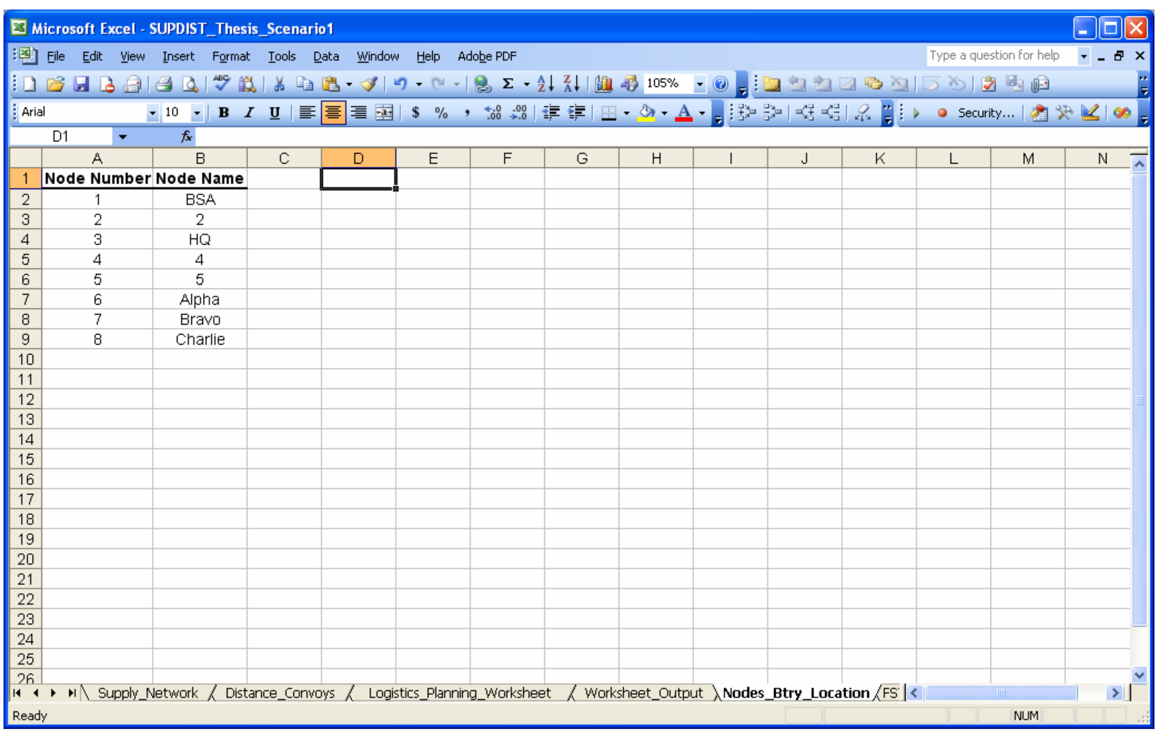
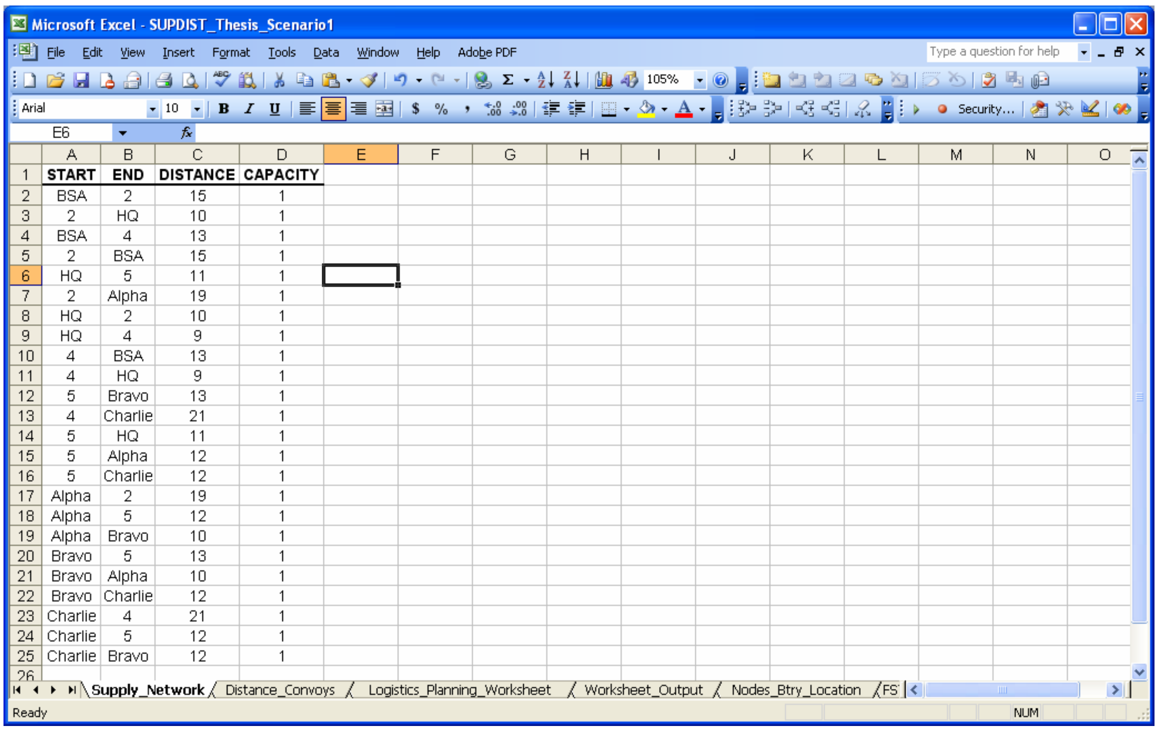


Figure 2. Node assignment and unit location based on network data from Figure 1.

Figure 2 above shows the node-specific data entries in Excel for the simplified network example in Figure 1. After the node data is entered, the user can then input the arc-specific data as displayed in Figure 3. Figure 3 has the column headers: “START “, “END”, “DISTANCE”, and “CAPACITY”. The “START” header is the node from which the convoy is departing and the “END” is the destination node. The “DISTANCE” column is the associated arc length between the “START” and “END” nodes. In this model, a “CAPACITY” equal to 1 means the road is open to for the convoy’s use.



START	END	DISTANCE	CAPACITY
BSA	2	15	1
2	HQ	10	1
BSA	4	13	1
2	BSA	15	1
HQ	5	11	1
2	Alpha	19	1
HQ	2	10	1
HQ	4	9	1
4	BSA	13	1
4	HQ	9	1
5	Bravo	13	1
4	Charlie	21	1
5	HQ	11	1
5	Alpha	12	1
5	Charlie	12	1
Alpha	2	19	1
Alpha	5	12	1
Alpha	Bravo	10	1
Bravo	5	13	1
Bravo	Alpha	10	1
Bravo	Charlie	12	1
Charlie	4	21	1
Charlie	5	12	1
Charlie	Bravo	12	1

Figure 3. Sample arc data entry for network in Figure 1 and node assignment from Figure 2.

C. COMPUTATIONAL PHASES

The decision support tool requires two phases of computational work to solve the optimal convoy: “presolve” and “solve”. In presolve, we use Dijkstra’s algorithm to determine the shortest path in the network between each pair of supply and demand nodes. We also enumerate a list of potential convoys from the BSA to all other

combinations of units and then calculate the associated distance for each. Thus, we pre-compute the shortest path route for every potential convoy. Because the supply distribution network data is relatively static (i.e., it changes infrequently), this pre-computation can be easily done without sacrificing performance.

In the solve phase, we use this list of potential convoys to determine the best combination of supplies to assign to each in a manner that satisfies operational constraints (such as the number of available vehicles) and meets the mission objectives.

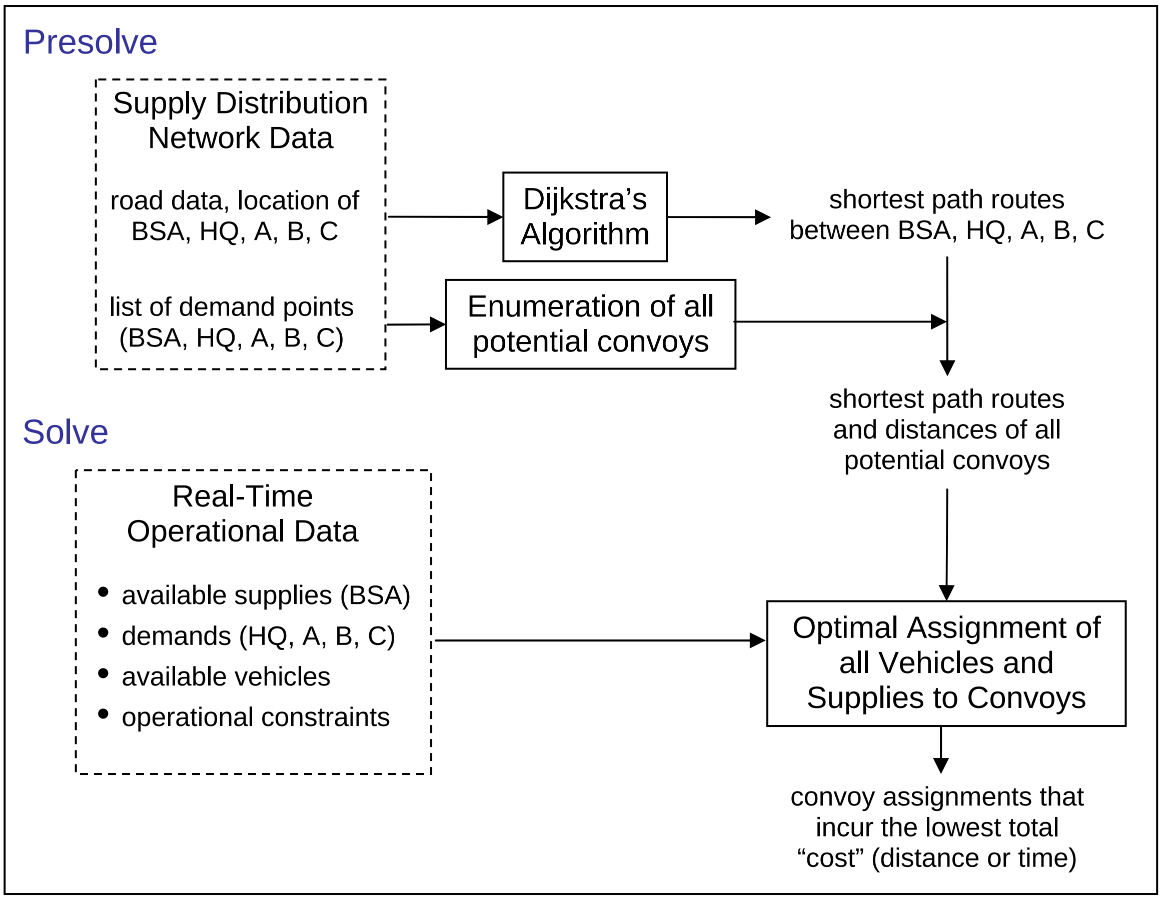


Figure 4. Computational Framework for convoy assignments.

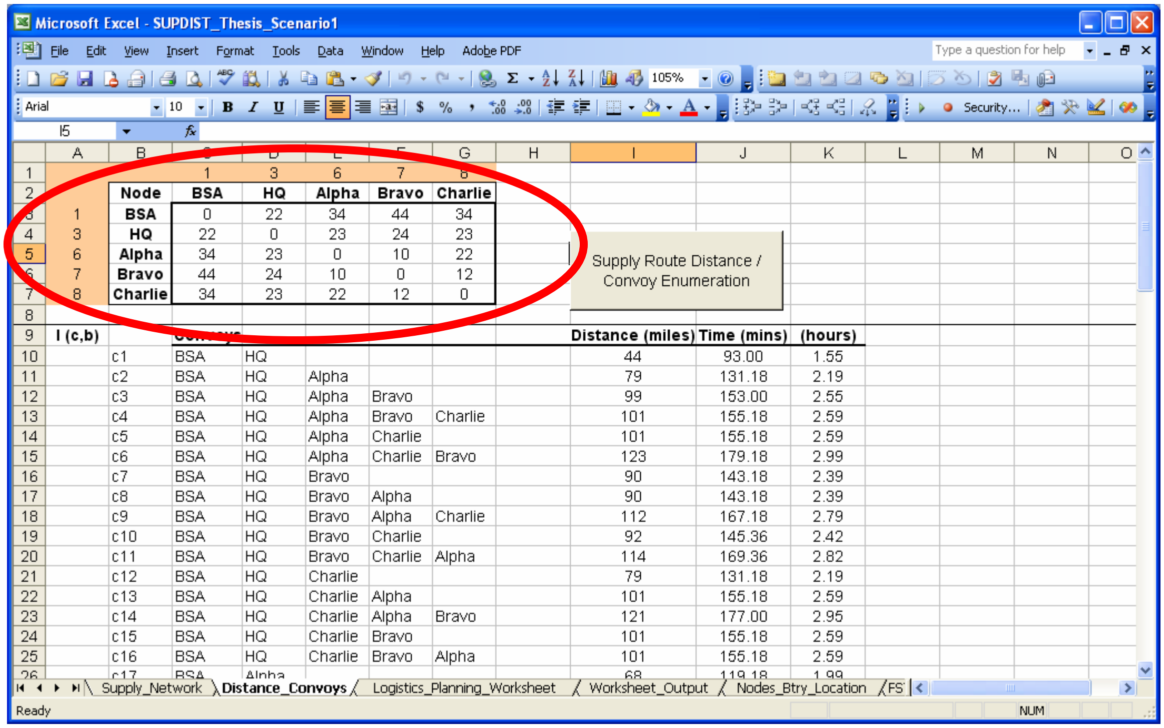
The figure above illustrates the overall process for identifying the optimal assignment of supplies to convoys. There are three key computational tasks used to obtain the optimal solution. They are: Dijkstra's algorithm, enumeration of all potential convoys, and the optimal assignment of supplies to convoys. We consider each in turn.

1. Dijkstra's Algorithm

This model uses a modified form of Dijkstra's algorithm (Ahuja et al., 1993, pp. 108-111). The algorithm finds the "shortest" path between each pair of supply and demand nodes. The "shortest path" is defined in terms of the round-trip distance from the supply node to the demand node(s) and back to the supply node. For this model we assume:

- The network is not directed;
- The network is strongly connected;
- Arc (road) lengths are integers; and
- All arc lengths are non-negative.

Each node in the network is assigned a distance label and a predecessor label. In the standard scenario, one node is the supply node and other nodes are demand nodes. During initialization of the algorithm, each node receives a large distance value. The value of the distance is based on the number of nodes, n, and the value of the largest arc length C. The distance values are initialized to nC. Also, the predecessor value is initialized at 0. From this point, the algorithm computes the distance matrix from each supply or demand node i to every other supply or demand node j. This first phase serves as a data verification and pre-solve tool. The resulting shortest-path data is stored in a distance matrix on the spreadsheet.



Node	BSA	HQ	Alpha	Bravo	Charlie
BSA	0	22	34	44	34
HQ	22	0	23	24	23
Alpha	34	23	0	10	22
Bravo	44	24	10	0	12
Charlie	34	23	22	12	0

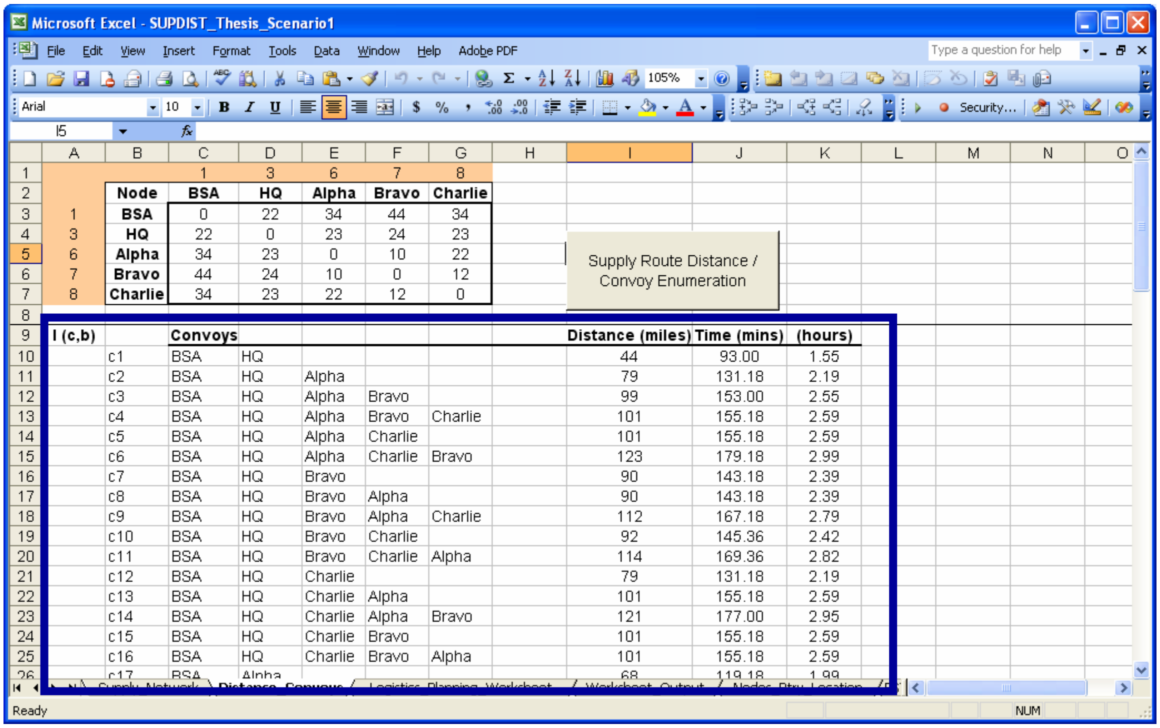
I (c,b)					Distance (miles)	Time (mins)	(hours)
c1	BSA	HQ			44	93.00	1.55
c2	BSA	HQ	Alpha		79	131.18	2.19
c3	BSA	HQ	Alpha	Bravo	99	153.00	2.55
c4	BSA	HQ	Alpha	Bravo Charlie	101	155.18	2.59
c5	BSA	HQ	Alpha	Charlie	101	155.18	2.59
c6	BSA	HQ	Alpha	Charlie Bravo	123	179.18	2.99
c7	BSA	HQ	Bravo		90	143.18	2.39
c8	BSA	HQ	Bravo	Alpha	90	143.18	2.39
c9	BSA	HQ	Bravo	Alpha Charlie	112	167.18	2.79
c10	BSA	HQ	Bravo	Charlie	92	145.36	2.42
c11	BSA	HQ	Bravo	Charlie Alpha	114	169.36	2.82
c12	BSA	HQ	Charlie		79	131.18	2.19
c13	BSA	HQ	Charlie	Alpha	101	155.18	2.59
c14	BSA	HQ	Charlie	Alpha Bravo	121	177.00	2.95
c15	BSA	HQ	Charlie	Bravo	101	155.18	2.59
c16	BSA	HQ	Charlie	Bravo Alpha	101	155.18	2.59

Figure 5. Screen shot of Excel spreadsheet output after executing "Supply Route Distance / Convoy Enumeration" button. The data encircled is the shortest distance from the BSA node to the designated demand nodes executing Dijkstra's algorithm.

Figure 5 presents the output from the pre-solve function. The matrix table lists the node locations for the BSA, HQ, Alpha, Bravo, and Charlie. The numbers in the matrix are the shortest distances between the nodes that are calculated by Dijkstra's algorithm. For example, from Alpha to Charlie, the distance is 22 miles.

2. Enumeration of Potential Convoys

For the purpose of this thesis, we define a potential convoy in terms of the list of demand nodes that are visited along with the order in which they are visited. For example, HQ – A – B represents a potential convoy that leaves the BSA, travels to HQ battery, then to Alpha battery, then to Bravo battery, and then returns to the BSA. For the demand nodes considered here, there are a total of 64 potential convoys.



	Node	BSA	HQ	Alpha	Bravo	Charlie
		1	3	6	7	8
1	BSA	0	22	34	44	34
3	HQ	22	0	23	24	23
6	Alpha	34	23	0	10	22
7	Bravo	44	24	10	0	12
8	Charlie	34	23	22	12	0

I (c,b)	Convoys					Distance (miles)	Time (mins)	(hours)
c1	BSA	HQ				44	93.00	1.55
c2	BSA	HQ	Alpha			79	131.18	2.19
c3	BSA	HQ	Alpha	Bravo		99	153.00	2.55
c4	BSA	HQ	Alpha	Bravo	Charlie	101	155.18	2.59
c5	BSA	HQ	Alpha	Charlie		101	155.18	2.59
c6	BSA	HQ	Alpha	Charlie	Bravo	123	179.18	2.99
c7	BSA	HQ	Bravo			90	143.18	2.39
c8	BSA	HQ	Bravo	Alpha		90	143.18	2.39
c9	BSA	HQ	Bravo	Alpha	Charlie	112	167.18	2.79
c10	BSA	HQ	Bravo	Charlie		92	145.36	2.42
c11	BSA	HQ	Bravo	Charlie	Alpha	114	169.36	2.82
c12	BSA	HQ	Charlie			79	131.18	2.19
c13	BSA	HQ	Charlie	Alpha		101	155.18	2.59
c14	BSA	HQ	Charlie	Alpha	Bravo	121	177.00	2.95
c15	BSA	HQ	Charlie	Bravo		101	155.18	2.59
c16	BSA	HQ	Charlie	Bravo	Alpha	101	155.18	2.59
c17	BSA	Alpha				68	119.18	1.99

Figure 6. Screen shot of the convoy enumeration. The boxed region contains the total convoy combinations with the total round trip distance. Time is calculated with a known travel speed of 60 miles per hour and a supply offload time of 45 minutes.

After Dijkstra's algorithm is complete, the program then enumerates each possible convoy route through demand nodes and takes the data from the distance matrix to calculate the convoy route's total distance. Figure 6 contains the convoy enumeration and the total convoy distance. From the figure, one can see that convoy c10 travels from the BSA to HQ, then leaves HQ and travels to Bravo, departs Bravo and travels to Charlie, and from Charlie returns to the BSA in a total distance of 92 miles. We assume a travel speed of speed of 60 miles per hour and a supply off load time of 45 minutes, thus the total time for this convoy is 145.36 minutes or 2.42 hours.

3. Convoy Assignment

The third step in solving for an optimal supply route is the convoy assignment. This step element uses both the Dijkstra shortest path distances and convoy route enumeration as input to a mathematical program that can be solved using General

Algebra Modeling Systems (GAMS). Given the available supplies, the battery demands, and the vehicles available for the convoy, we use GAMS to solve for the optimal convoy(s), defined to be the minimal convoy route that satisfies all the demands at all the battery locations. We present the mathematical program, in NPS "Standard Form", used to solve the optimal convoy assignment problem:

a. Index Sets

k	classes of supply
b	batteries; Alpha "A", Bravo "B", Charlie "C", Headquarters "HQ"
v	vehicle type; HMMWV and MTVR
c	convoy route *c*

b. Data [Units]

d_c	total distance of convoy route *c* [miles]
r_{kb}	requirement for class of supply *k* at battery *b* [k-units]
p_v	available pool of vehicles of type *v* [cardinality]
w_cap_v	weight capacity of vehicle type *v* [pounds]
q_cap_v	volume capacity of vehicle type *v* [cubic feet]
w_k	weight per package per class of supply *k* [pounds]
t_c	round trip travel time for convoy route *c* [hours]

c. Decision Variables [Units]

$X_{k,c,b}$	quantity of supply class *k* loaded on convoy route *c* destined for battery *b* [k-units]
$Y_{v,c}$	number of vehicles of type *v* assigned to convoy route c [cardinal]
Z_c	1 if convoy route *c* is used [binary]

d. *Formulation*

$$\underset{X,Y,Z}{MIN} \sum_c d_c Z_c \qquad \text{(C0)}$$

$$Z_c \le \sum_v Y_{v,c} \qquad \text{(C1)}$$

$$\sum_v Y_{v,c} \le Z_c \sum_v p_v \qquad \text{(C2)}$$

$$\sum_c X_{k,c} \ge \sum_b r_{k,b}, \qquad \forall k \qquad \text{(C3)}$$

$$\sum_c X_{k,c,b} I_{c,b} \ge r_{k,b}, \qquad \forall k,b \qquad \text{(C4)}$$

$$\sum_k X_{k,c} w_k \le \sum_v Y_{v,c} w\_cap_v, \qquad \forall c \qquad \text{(C5)}$$

$$\sum_k X_{k,c} q_k \le \sum_v Y_{v,c} q\_cap_v, \qquad \forall c \qquad \text{(C6)}$$

$$\sum_c Y_{v,c} \le p_v, \qquad \forall v \qquad \text{(C7)}$$

4. Discussion

The objective function, (C0), calculates the total length of all convoy routes traveled. Constraints (C1) and (C2) maintain consistency between $Y_{v,c}$ and Z_c. If there are no vehicles available then the convoy cannot be selected, thus if $Y_{v,c}$ is equal to 0, then Z_c has to equal 0. Conversely, if there are vehicles available, then a convoy of type *c* can be selected from $I_{c,b}$. Constraint (C3) ensures that the amount of supplies loaded on convoy *c* satisfies the total amount of supplies demanded. Constraint (C4) selects the correct convoy route *c* from the $I_{c.b}$ matrix and validates that the amount loaded on the convoy will meet the demand at battery *b*. Constraints (C5) and (C6) impose restrictions on the amount of materials loaded on the vehicles based on the type of vehicle and its capacities. The last constraint (C7) determines the amount of vehicles per convoy route *c*. The number of vehicles assigned to the convoy cannot exceed the number of available vehicles.

For the purpose of this thesis, we are primarily concerned with the convoys that result in the lowest total travel distance. However, the logistics officer may be interested in other criteria, and the model and interface here are easily adapted. For example, to find the convoys that result in the shortest "time in the field" we can use travel times for convoy distance, d_c values, as another objective function: $\underset{X,Y,Z}{MIN} \quad \underset{C}{MAX}\left\{d_c\right\}$, which requires a reformulation:

$$\underset{W,X,Y,Z}{MIN} \quad W \qquad \text{(C0')}$$

$$s.t. \qquad W \geq d_c Z_c \qquad \forall c \qquad \text{(C8)},$$

along with (C1) through (C7). Another objective function that could be implemented is: $\underset{X,Y,Z}{MIN} \quad \sum_c d_c \sum_v Y_{v,c}$. This objective function calculates total vehicle-miles traveled and might be an adequate surrogate for risk. The scenario in the next chapter focuses exclusively on minimizing travel distance.

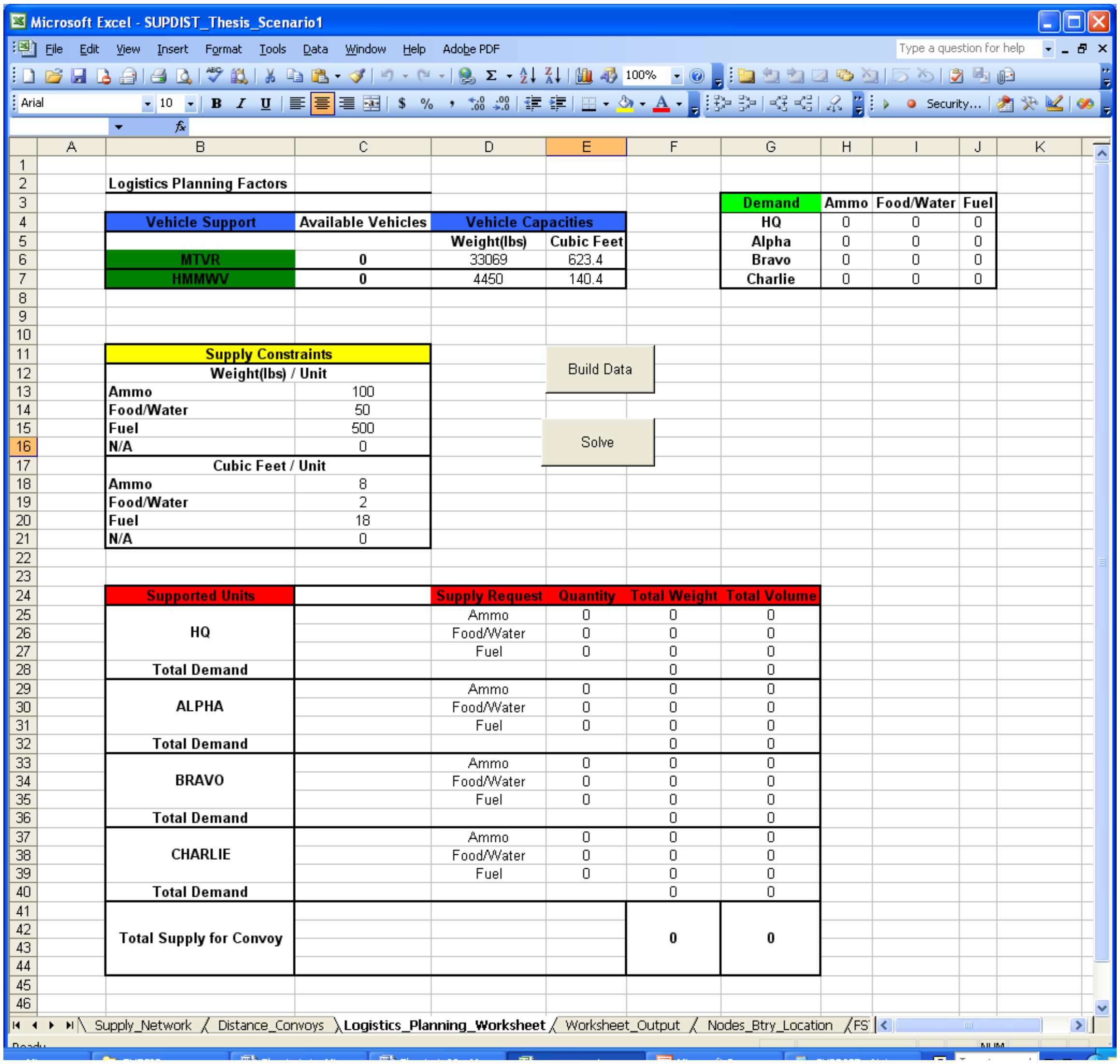


Figure 7. Screen shot of the Logistics Planning Worksheet.

Figure 7 shows the spreadsheet for this second phase, including the data fields necessary to calculate the convoy route. Once the logistics officer completes his data entries for available vehicles and the supported units' demands, the "Build Data" button then generates two data files to be used as input for convoy building. The "Solve" button will then use the two files and solve for the optimal convoy route from Figure 6. The data entries, along with the pre-solve data, are used as input into the GAMS. The GAMS

program uses the data to calculate the total amount of vehicles required to support the supply demands and also determines the convoy(s) with the optimal route(s) to distribute the supplies.

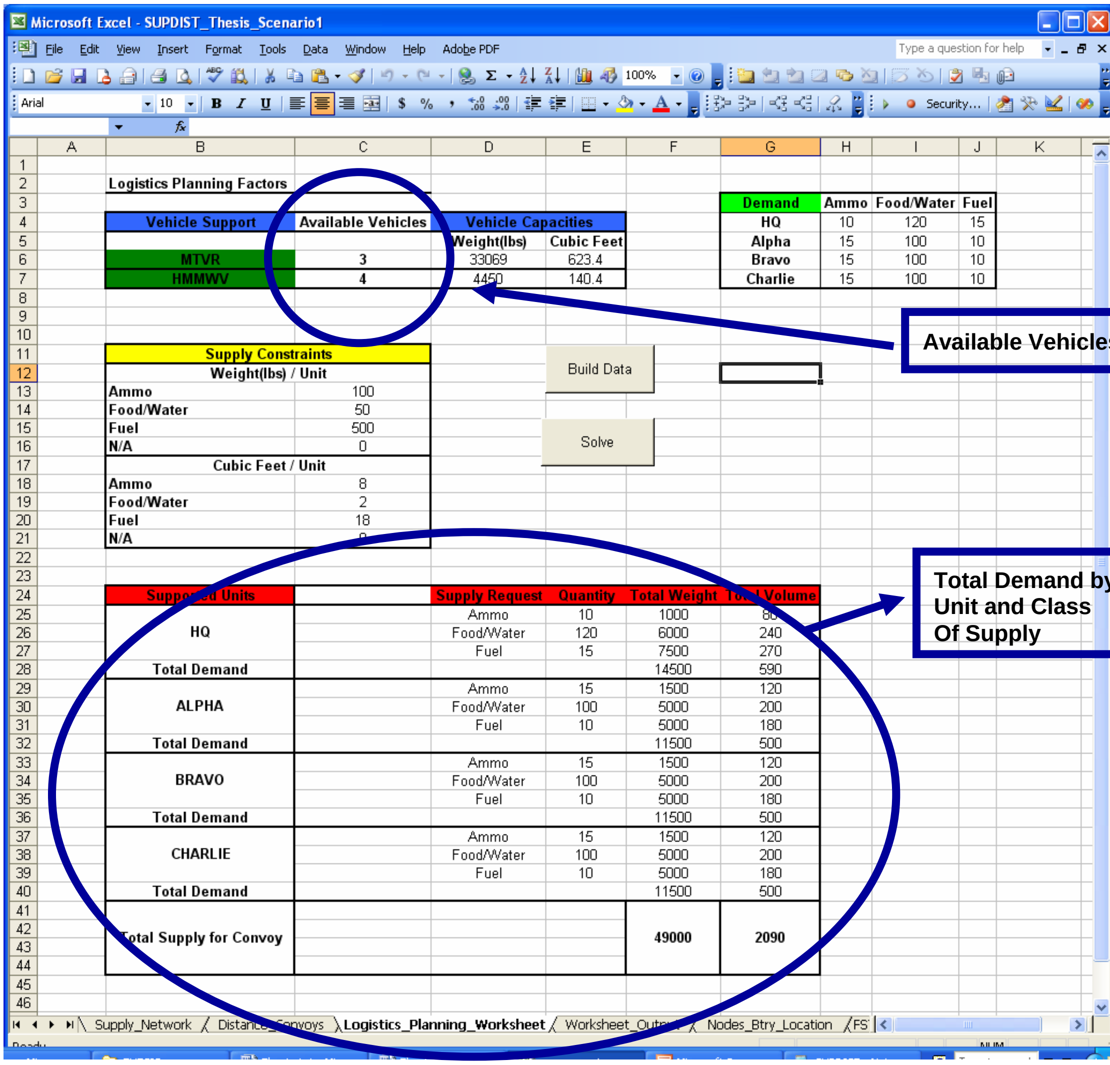


Figure 8. Sample screen shot of a completed Logistics Planning Worksheet. After the data is entered, the user will click the "Build Data" button to capture the vehicles available to support the convoy as well as the total supply demanded by battery. After the data is stored in the GAMS files, the "Solve" button is used to run the GAMS program to find the optimal convoy.

The figure above displays the supply demands by class of supply and by the requesting battery. The figure also displays the type of vehicle and the number of that type of vehicle that is available for the convoy.

D. MODEL OUTPUT

Based on the initial network data, the first phase of the program calculates the pre-solve data using Dijkstra's algorithm and the enumeration of convoys with round trip distances and convoy times. The first phase data is then used as input to the second phase.

The second phase then uses the data files created from the first phase and the following is used to determine the optimal distribution route solved by GAMS:

- Distance of the supply distribution network;
- Total demand for supplies at the demand nodes;
- Number of vehicles available for the convoy to satisfy demands;
- Total distance convoy has to travel; and
- Optimal route and order to distribute supplies that meets demand requirements

Based on the number of vehicles, their respective capacities, and the total amount of supplies demanded, GAMS will then determine if a feasible solution exists. If one does not, GAMS will report an error and that no solution is available. If the data produces a feasible answer, then a text file is created and will then be opened on the desktop as shown in Figure 9.

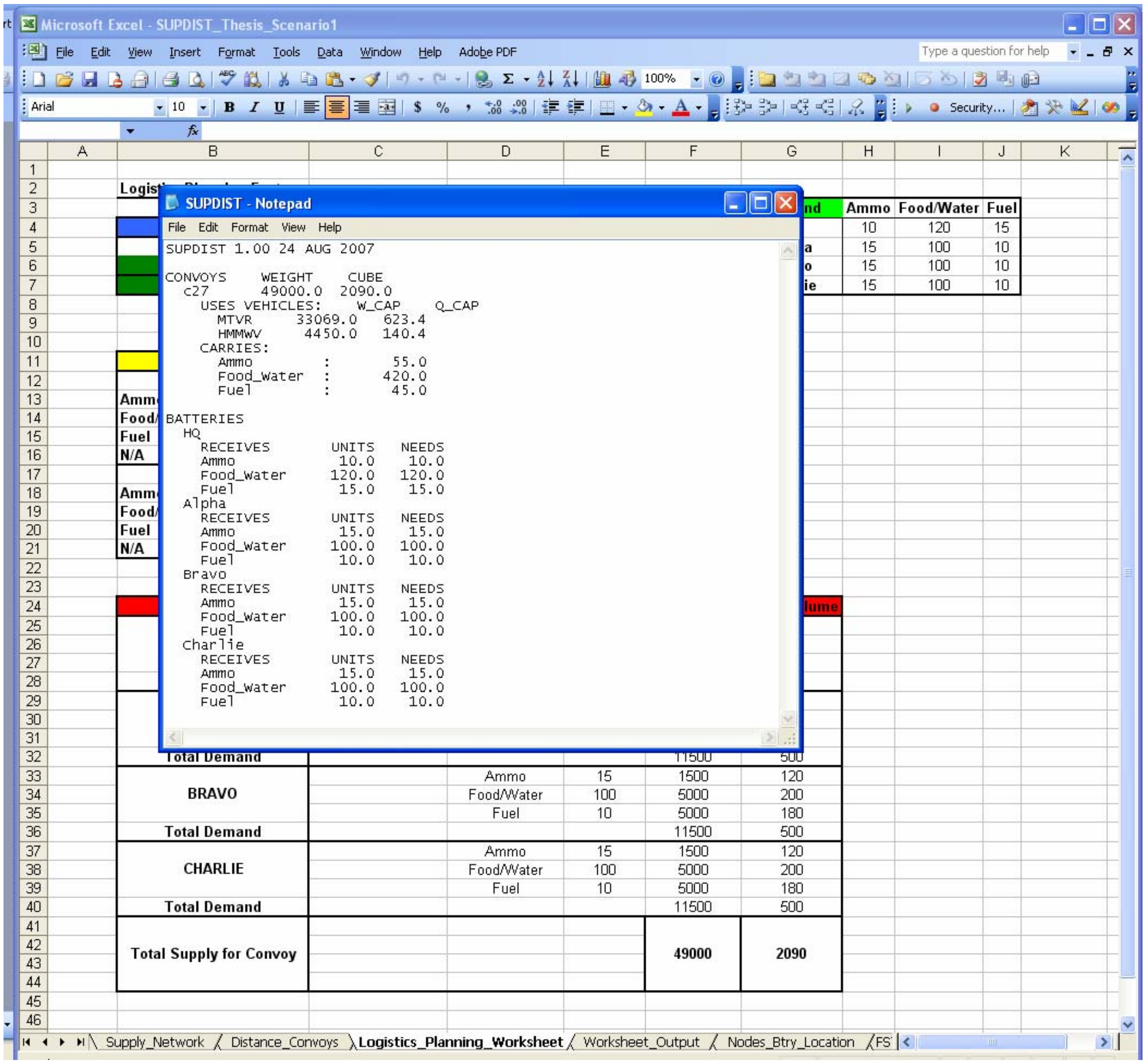


Figure 9. Screen shot of the Logistics Planning Worksheet after GAMS has been executed. The notepad window contains the optimal solution to include the convoy number, the supplies demanded, and the supplies received.

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IV. SCENARIO AND RESULTS

This chapter presents two scenarios that illustrate both the application and value of the decision support tool for building optimal re-supply convoys.

A. SCENARIO 1: SAMPLE TRAINING SCENARIO

The first scenario considers the characteristics of a USMC artillery battalion as described in Chapter I regarding force size and typical mission requirements. The battalion is located in a small notional training area (Figure 9). The current training factors involve static (no movement) shooting of the three firing batteries that are in direct fire support of an infantry regiment. The headquarters (HQ) battery supports the firing missions through command and control and communications support. Since the HQ battery is in support, their personnel is moving from node to node through the network, thus their supply support needs emphasize fuel as well as food and water. Since the firing batteries are not moving, their fuel consumption is low and fuel will not be in high demand. However, ammunition, food, and water are required to sustain the Marines. The decision the logistics officer has to make is to determine the convoys that deliver the demanded supplies in the shortest convoy route with the number of available vehicles to support the convoy.

1. Supply Distribution Network 1

The distribution network for the first scenario is the network displayed in Figure 10 and contains the data from Figure 11 and Figure 12. The network below contains 14 arcs (28 to include two-way traffic). Each arc has a designated length (distance). We assume the supply node, BSA, has an infinite amount of supply to satisfy the demands at the various battery locations. Each demand node has an associated demand, a negative value shown in brackets. The requirements are broken into classes of supply; those classes are Food / Water, Fuel, and Ammunition. Each battery has a certain demand for each. These demands are:

•	HQ Battery:	Food / Water	125 units
		Fuel	20 units
		Ammunition	22 units
•	Alpha Battery:	Food / Water	120 units
		Fuel	30 units
		Ammunition	50 units
•	Bravo Battery:	Food / Water	120 units
		Fuel	35 units
		Ammunition	42 units
•	Charlie Battery:	Food / Water	120 units
		Fuel	33 units
		Ammunition	54 units

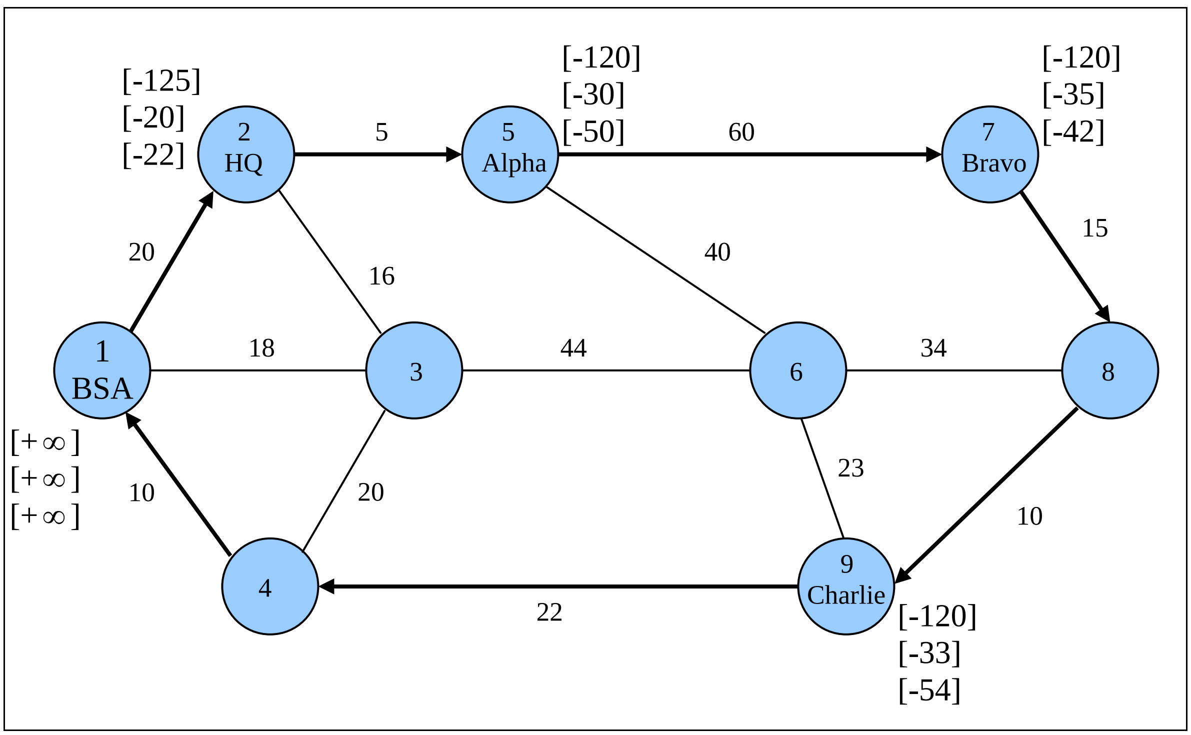
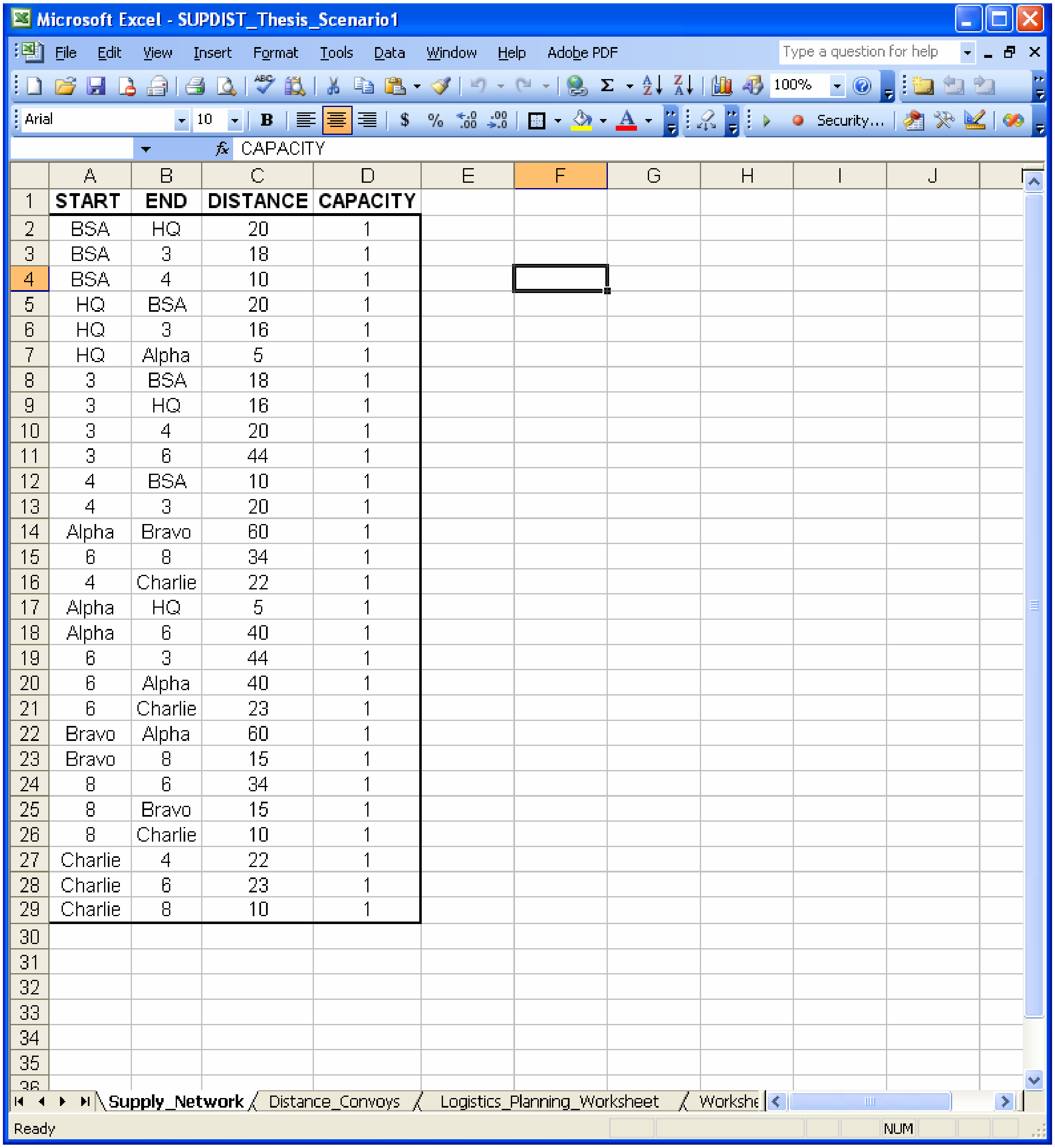


Figure 10. A simple network and potential supply distribution route. The numbers in brackets correspond to the supply of Food/Water, Fuel, and Ammunition for that node, where negative values denote demand. The arrows direct the route from the BSA to HQ battery, then to Alpha, to Bravo, then to node 8, to Charlie, and returns to the BSA.

By visual inspection, one can see how a single convoy could support the four units. The displayed solution consists a single convoy that carries a total supply load of 771 units (total weight of 100,050 pounds and requires 4,438 cubic feet of storage) to satisfy the demand requirements. The convoy travels a total distance of 142 miles. This solution requires the convoy to use six Medium Tactical Vehicle Replacements (MTVR) and five High Mobility Multipurpose Weighted Vehicle (HMMWV, Humvee). Provided that the 11 vehicles are available, and the total travel distance is acceptable, then this route represents a feasible solution.

The question is: Is this the “best” solution? Moreover, does this model and decision support tool offer a better solution to the logistics officer in order to plan and coordinate convoys to support the demands of the forward deployed units?

For this scenario and the results we are trying to achieve, our model solves for the shortest route that the convoy(s) must travel in order to satisfy demand requirements. The figure below contains the network data that correspond to Figure 10.



START	END	DISTANCE	CAPACITY
BSA	HQ	20	1
BSA	3	18	1
BSA	4	10	1
HQ	BSA	20	1
HQ	3	16	1
HQ	Alpha	5	1
3	BSA	18	1
3	HQ	16	1
3	4	20	1
3	6	44	1
4	BSA	10	1
4	3	20	1
Alpha	Bravo	60	1
6	8	34	1
4	Charlie	22	1
Alpha	HQ	5	1
Alpha	6	40	1
6	3	44	1
6	Alpha	40	1
6	Charlie	23	1
Bravo	Alpha	60	1
Bravo	8	15	1
8	6	34	1
8	Bravo	15	1
8	Charlie	10	1
Charlie	4	22	1
Charlie	6	23	1
Charlie	8	10	1

Figure 11. Network data entry for Scenario 1.

2. Data Input for Scenario 1

Figure 12 represents the supply support requested by the HQ battery and the three firing batteries based on the training scenario.

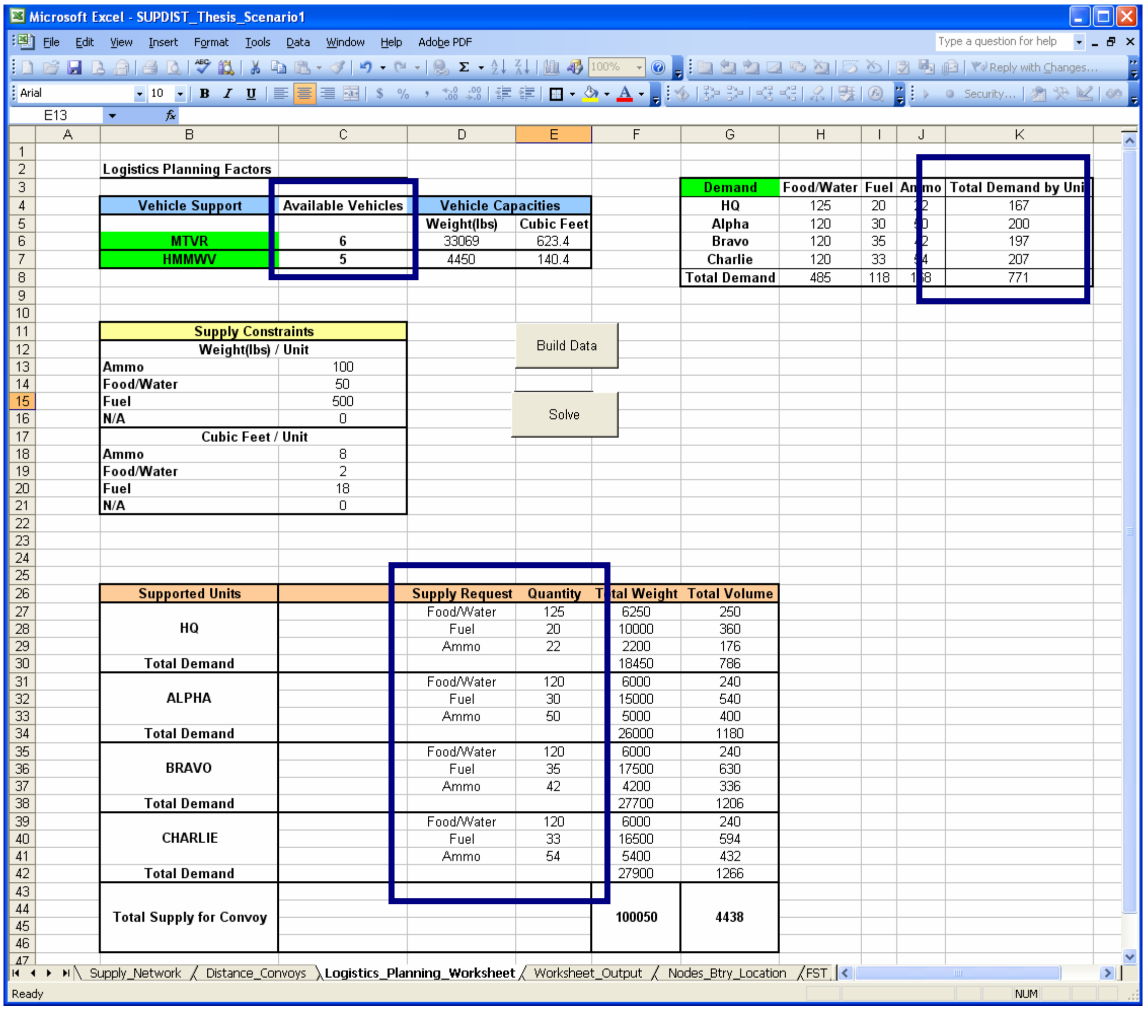


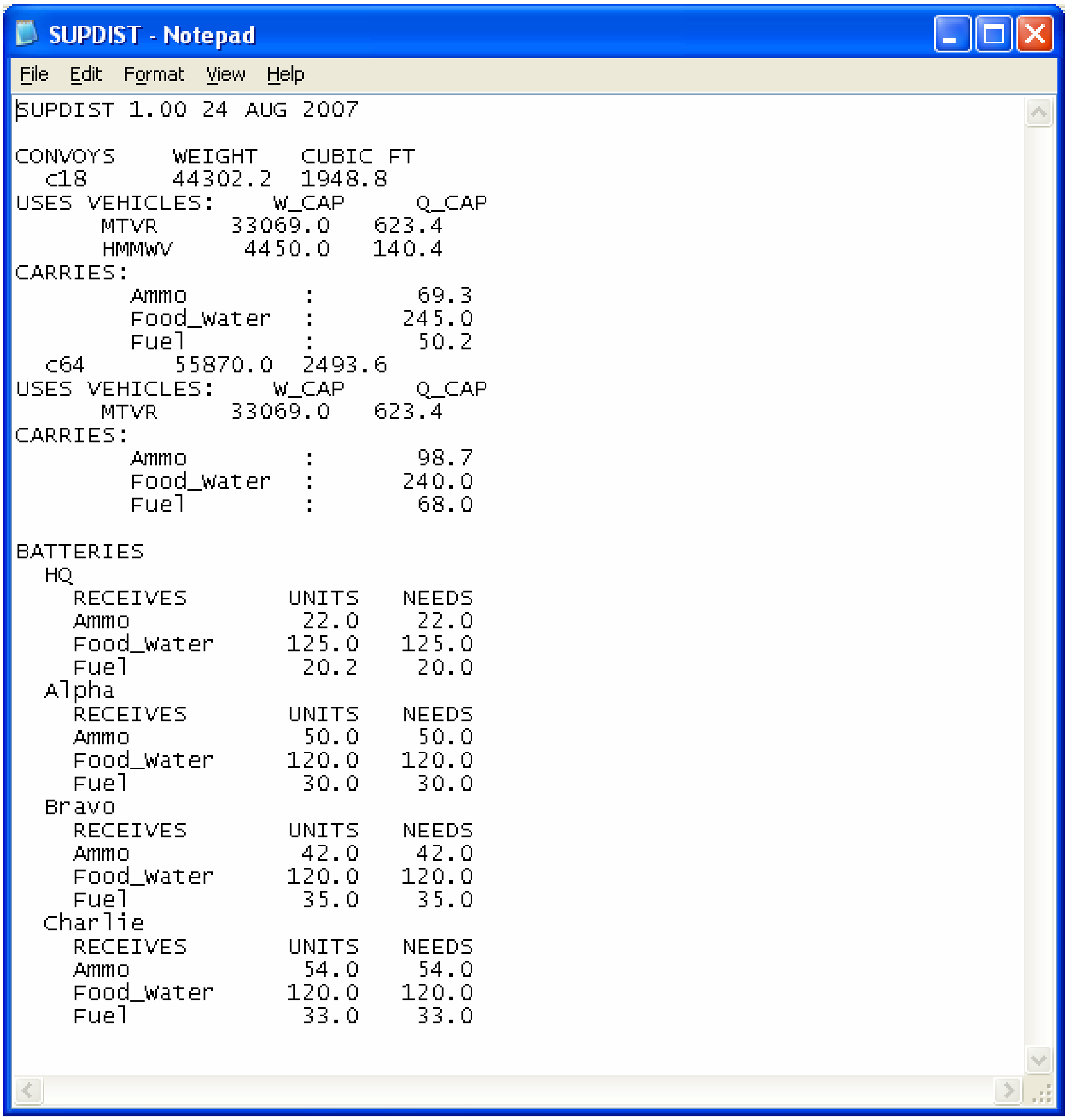
Figure 12. The Logistics Planning Worksheet. Above are the supply requests from the units as well as the vehicles available to support the convoy.

The figure above is the Logistics Planning Worksheet. On this sheet the logistics officer enters the supply requests. He also enters the number of vehicles, by type, that are available to support the convoy. After all the data is entered, the "Build Data" button

creates the GAMS data files. Once the files are created, the "Solve" button then runs the GAMS program. The GAMS program uses the pre-solve data with the data above and determines the convoy route that is optimal.

B. RESULTS TO SCENARIO 1

The results to Scenario 1 are given in the figure below:



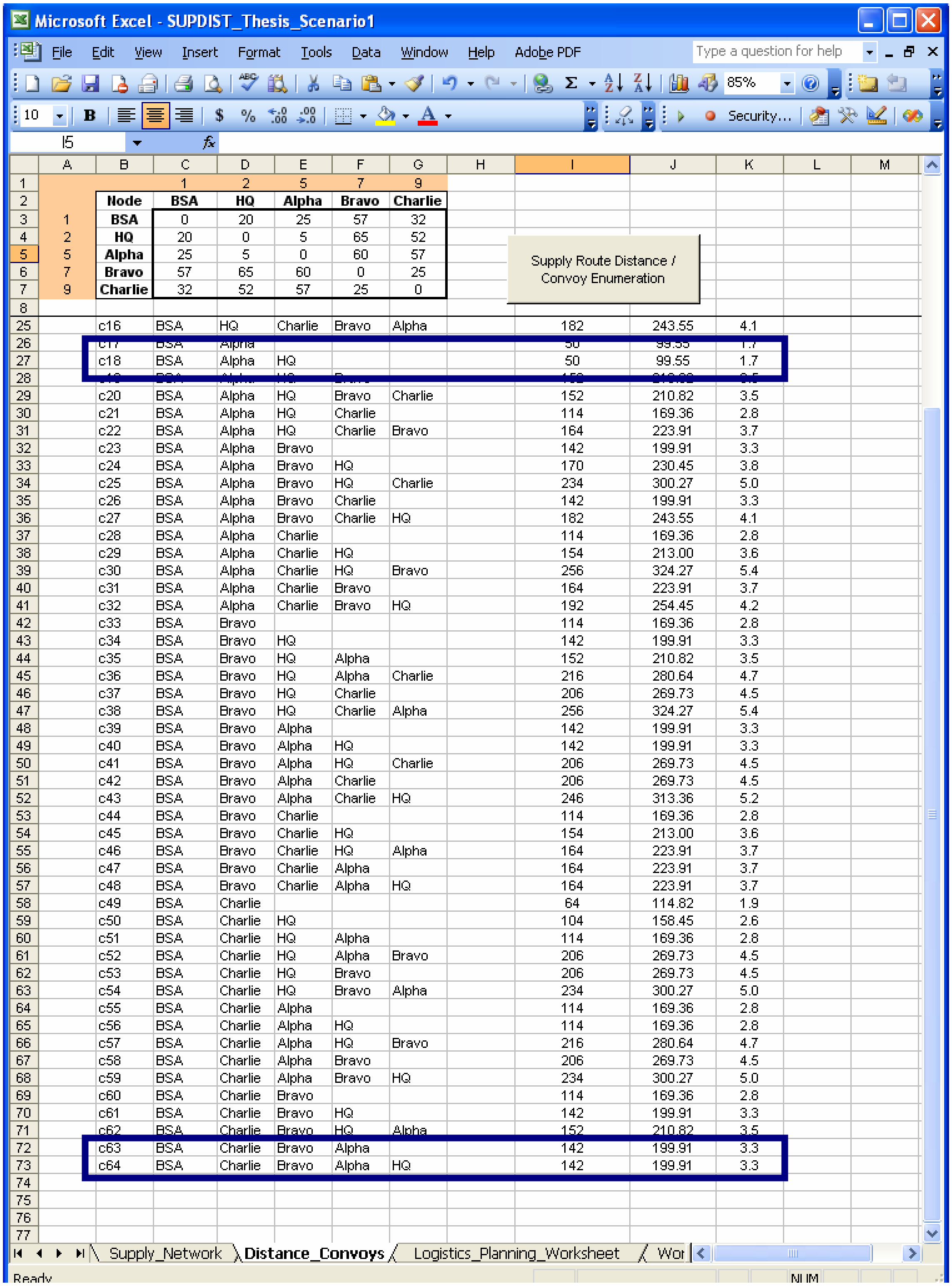

```
SUPDIST 1.00 24 AUG 2007

CONVOYS     WEIGHT    CUBIC FT
  c18       44302.2   1948.8
USES VEHICLES:     W_CAP      Q_CAP
      MTVR      33069.0   623.4
      HMMWV      4450.0   140.4
CARRIES:
        Ammo          :        69.3
        Food_Water    :       245.0
        Fuel          :        50.2
  c64       55870.0   2493.6
USES VEHICLES:     W_CAP      Q_CAP
      MTVR      33069.0   623.4
CARRIES:
        Ammo          :        98.7
        Food_Water    :       240.0
        Fuel          :        68.0

BATTERIES
  HQ
    RECEIVES       UNITS    NEEDS
    Ammo            22.0     22.0
    Food_Water     125.0    125.0
    Fuel            20.2     20.0
  Alpha
    RECEIVES       UNITS    NEEDS
    Ammo            50.0     50.0
    Food_Water     120.0    120.0
    Fuel            30.0     30.0
  Bravo
    RECEIVES       UNITS    NEEDS
    Ammo            42.0     42.0
    Food_Water     120.0    120.0
    Fuel            35.0     35.0
  Charlie
    RECEIVES       UNITS    NEEDS
    Ammo            54.0     54.0
    Food_Water     120.0    120.0
    Fuel            33.0     33.0
```

Figure 13. Output from the GAMS program.

Figure 13 contains the optimal supply route that was solved by the GAMS program. From the top of the figure under "CONVOYS" it lists both c18 and c64 as the optimal convoys. The two convoy numbers are represented on the "Distance_Convoys" worksheet shown below.



Microsoft Excel - SUPDIST_Thesis_Scenario1

	A	B	C	D	E	F	G	H	I	J	K
1			1	2	5	7	9				
2		Node	BSA	HQ	Alpha	Bravo	Charlie				
3	1	BSA	0	20	25	57	32				
4	2	HQ	20	0	5	65	52				
5	5	Alpha	25	5	0	60	57				
6	7	Bravo	57	65	60	0	25				
7	9	Charlie	32	52	57	25	0				
8											
25		c16	BSA	HQ	Charlie	Bravo	Alpha		182	243.55	4.1
26		c17	BSA	Alpha					50	99.55	1.7
27		c18	BSA	Alpha	HQ				50	99.55	1.7
28		c19	BSA	Alpha	HQ	Bravo			152	210.82	3.5
29		c20	BSA	Alpha	HQ	Bravo	Charlie		152	210.82	3.5
30		c21	BSA	Alpha	HQ	Charlie			114	169.36	2.8
31		c22	BSA	Alpha	HQ	Charlie	Bravo		164	223.91	3.7
32		c23	BSA	Alpha	Bravo				142	199.91	3.3
33		c24	BSA	Alpha	Bravo	HQ			170	230.45	3.8
34		c25	BSA	Alpha	Bravo	HQ	Charlie		234	300.27	5.0
35		c26	BSA	Alpha	Bravo	Charlie			142	199.91	3.3
36		c27	BSA	Alpha	Bravo	Charlie	HQ		182	243.55	4.1
37		c28	BSA	Alpha	Charlie				114	169.36	2.8
38		c29	BSA	Alpha	Charlie	HQ			154	213.00	3.6
39		c30	BSA	Alpha	Charlie	HQ	Bravo		256	324.27	5.4
40		c31	BSA	Alpha	Charlie	Bravo			164	223.91	3.7
41		c32	BSA	Alpha	Charlie	Bravo	HQ		192	254.45	4.2
42		c33	BSA	Bravo					114	169.36	2.8
43		c34	BSA	Bravo	HQ				142	199.91	3.3
44		c35	BSA	Bravo	HQ	Alpha			152	210.82	3.5
45		c36	BSA	Bravo	HQ	Alpha	Charlie		216	280.64	4.7
46		c37	BSA	Bravo	HQ	Charlie			206	269.73	4.5
47		c38	BSA	Bravo	HQ	Charlie	Alpha		256	324.27	5.4
48		c39	BSA	Bravo	Alpha				142	199.91	3.3
49		c40	BSA	Bravo	Alpha	HQ			142	199.91	3.3
50		c41	BSA	Bravo	Alpha	HQ	Charlie		206	269.73	4.5
51		c42	BSA	Bravo	Alpha	Charlie			206	269.73	4.5
52		c43	BSA	Bravo	Alpha	Charlie	HQ		246	313.36	5.2
53		c44	BSA	Bravo	Charlie				114	169.36	2.8
54		c45	BSA	Bravo	Charlie	HQ			154	213.00	3.6
55		c46	BSA	Bravo	Charlie	HQ	Alpha		164	223.91	3.7
56		c47	BSA	Bravo	Charlie	Alpha			164	223.91	3.7
57		c48	BSA	Bravo	Charlie	Alpha	HQ		164	223.91	3.7
58		c49	BSA	Charlie					64	114.82	1.9
59		c50	BSA	Charlie	HQ				104	158.45	2.6
60		c51	BSA	Charlie	HQ	Alpha			114	169.36	2.8
61		c52	BSA	Charlie	HQ	Alpha	Bravo		206	269.73	4.5
62		c53	BSA	Charlie	HQ	Bravo			206	269.73	4.5
63		c54	BSA	Charlie	HQ	Bravo	Alpha		234	300.27	5.0
64		c55	BSA	Charlie	Alpha				114	169.36	2.8
65		c56	BSA	Charlie	Alpha	HQ			114	169.36	2.8
66		c57	BSA	Charlie	Alpha	HQ	Bravo		216	280.64	4.7
67		c58	BSA	Charlie	Alpha	Bravo			206	269.73	4.5
68		c59	BSA	Charlie	Alpha	Bravo	HQ		234	300.27	5.0
69		c60	BSA	Charlie	Bravo				114	169.36	2.8
70		c61	BSA	Charlie	Bravo	HQ			142	199.91	3.3
71		c62	BSA	Charlie	Bravo	HQ	Alpha		152	210.82	3.5
72		c63	BSA	Charlie	Bravo	Alpha			142	199.91	3.3
73		c64	BSA	Charlie	Bravo	Alpha	HQ		142	199.91	3.3

Figure 14. The optimal convoy route, total convoy distance, and the total time it will take to complete the convoy.

As we can see, the convoy solution given by our model is not the same as the single convoy obtained from visual inspection in Figure 10. Rather, the optimal solution uses two convoys. The first convoy, c18, distributes supplies to the following batteries in this order: the BSA to Alpha battery, then to the HQ battery, and back to the BSA. Based on the data from Figure 12, convoy c18 requires the use of seven total vehicles (two MTVR's and the five total HMMWV's). Convoy c64 consists of the remaining four MTVR's and travels the following route: departs the BSA to visit Charlie battery, followed by Bravo battery, then to Alpha battery, then finally to HQ battery before returning to the BSA. As we see from Figure 12, each battery receives their requested amount (the requested amount is shown under the "NEEDS" column). The delivery information is shown under the "UNITS" column in Figure 12.

The simple solution in Figure 10 yielded a total distance of 142 miles and a total time of 3.3 hours. In contrast, our model finds not only the shortest point to point distance (Dijkstra's algorithm), but also the minimal the total vehicle distance. Total vehicle distance is simply the total distance of the convoy's route multiplied by the number of vehicles assigned to the convoy. The total vehicle distance from the single convoy as depicted in Figure 9 is 142 miles multiplied by the 11 vehicles making the total vehicle distance for the convoy 1,562 miles. Since this is a relatively simple network, a visual inspection and this solution might suffice, however it is not optimal. The optimal solution, obtained from our model, shows that convoy c18 uses seven vehicles and travels a route distance of 50 miles, making the total vehicle distance 350 miles. Convoy c64 uses four vehicles and has a route distance of 142 miles, thus making the total vehicle distance 568 miles. The difference between the two solutions is 644 vehicle miles, a savings of 644/1562 = 41.2% of the total vehicle distance. The decision support tool does make the solution better.

Not all networks are as simple as presented in Scenario 1. However, this scenario provides a simple network to explain the model as well as demonstrate the use of the Excel spreadsheets and the GAMS program, while also illustrating its potential benefit. Scenario 2 consists of a larger, more complex network where a feasible solution may not be available from visual inspection.

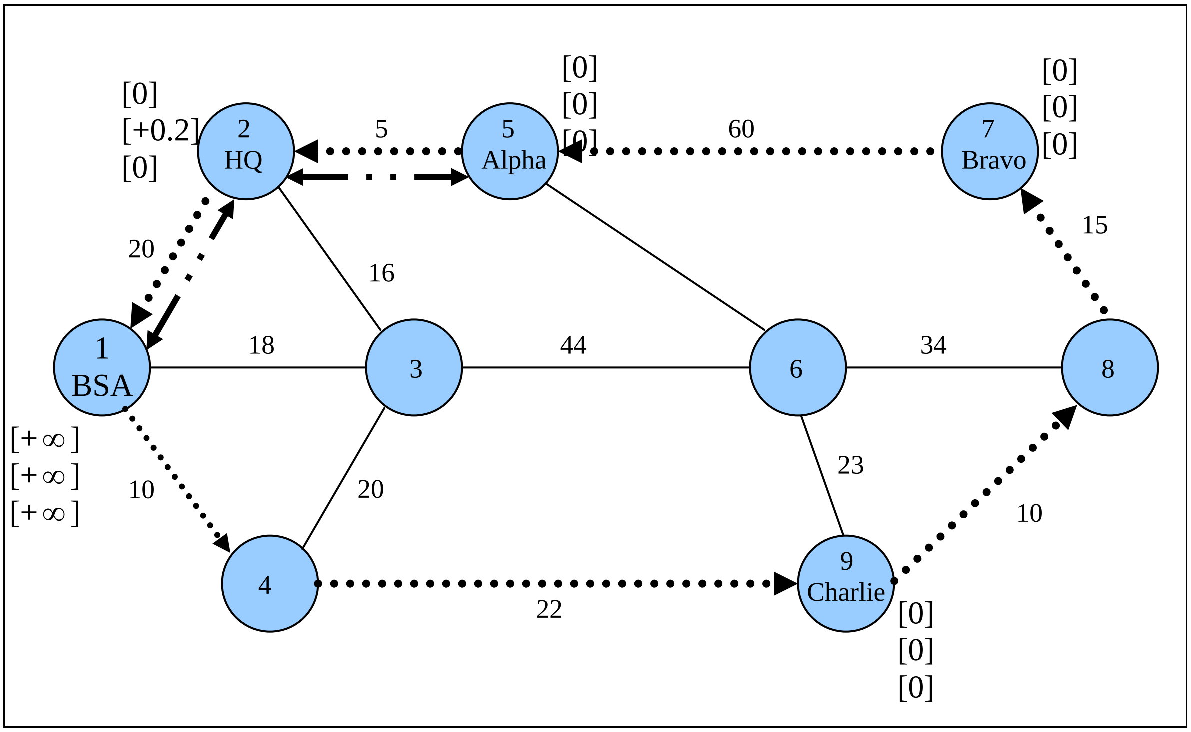


Figure 15. Optimal solution to the simple network. The double headed arrows represent convoy c18. The dotted line segments represent convoy c64 with the direction of the convoy and the order in which the batteries are visited. Also note that all the brackets contain "0" which means all demands were met with HQ battery receiving a portion of extra fuel.

C. SCENARIO 2: DIRECT SUPPORT OF INFANTRY REGIMENT

This scenario represents a more realistic deployment in which the battalion is in direct support of the infantry regiment. Contact with the enemy forces has the infantry units moving throughout the (AO). Due to the enemy movement and reactions of the infantry units, the firing batteries must be ready to deliver ground fires as well as maneuver into more advantageous positions to provide fire support. This requires the batteries to maintain sufficient amounts of ammunition and to ensure their fuel levels will support their movement to any location. Thus, ammunition and fuel become the top priority with food and water being re-supplied as needed and when vehicles are available after distributing ammunition and fuel requirements. The HQ battery will be in direct support of the firing batteries and assist in command and control of the firing batteries and provide logistical support. Since the HQ battery has to maintain contact and be

prepared to assist anywhere in the AO, they have a high priority for fuel. Both classes I and V (Food/Water and Ammunition) will be delivered as needed.

1. Supply Distribution Network 2

The distribution network for the second scenario is a notional network depicted in Figure 16. The network displayed in the below figure represents the (AO) for the artillery battalion, the nodes that are occupied by the batteries are demand nodes, and the nodes that are not occupied by the HQ battery or any of the three firing batteries are transshipment nodes. The arcs connecting the nodes are the available roads in the supply distribution network that the convoys must navigate. This scenario network is more complex than in the first scenario, and there is not an obvious best candidate for a convoy route. However, our tool provides a solution that is optimal given the constraints that will satisfy the demand requirements in the shortest amount of total vehicle distance.

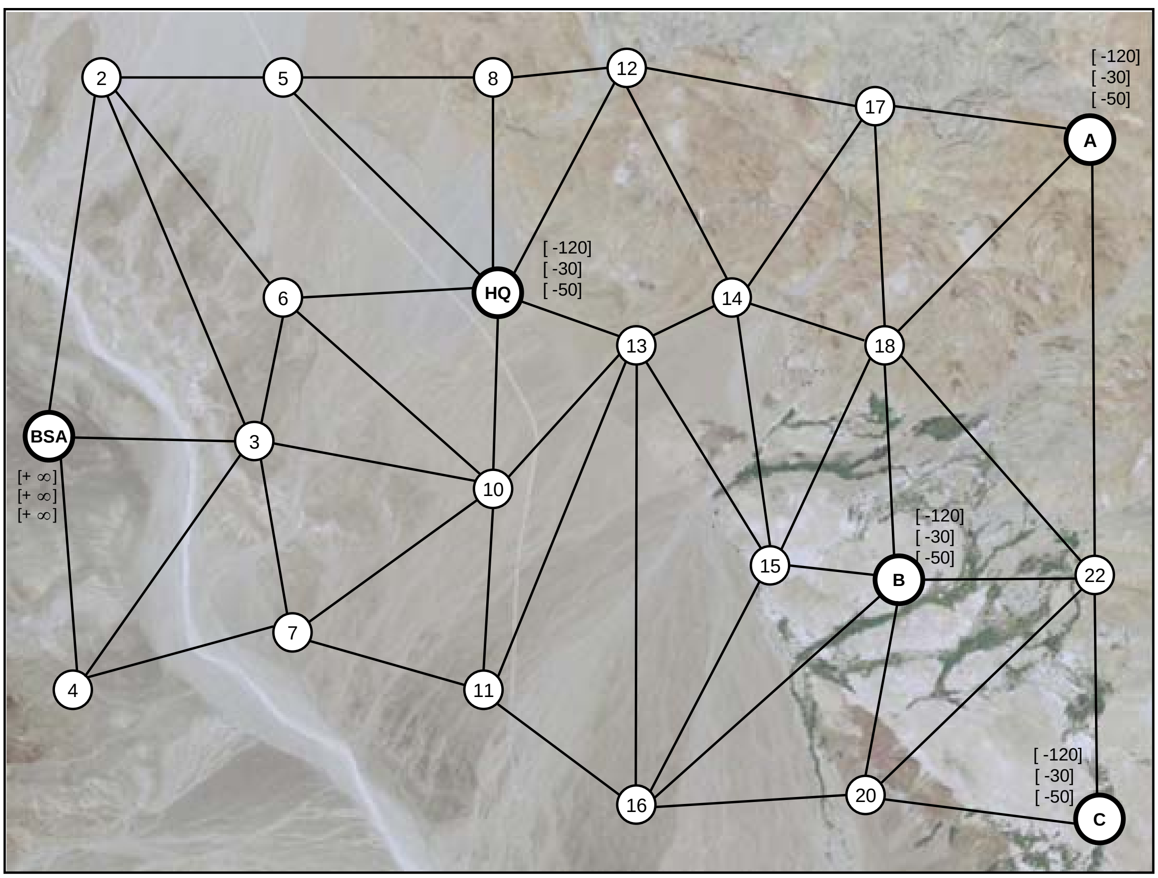
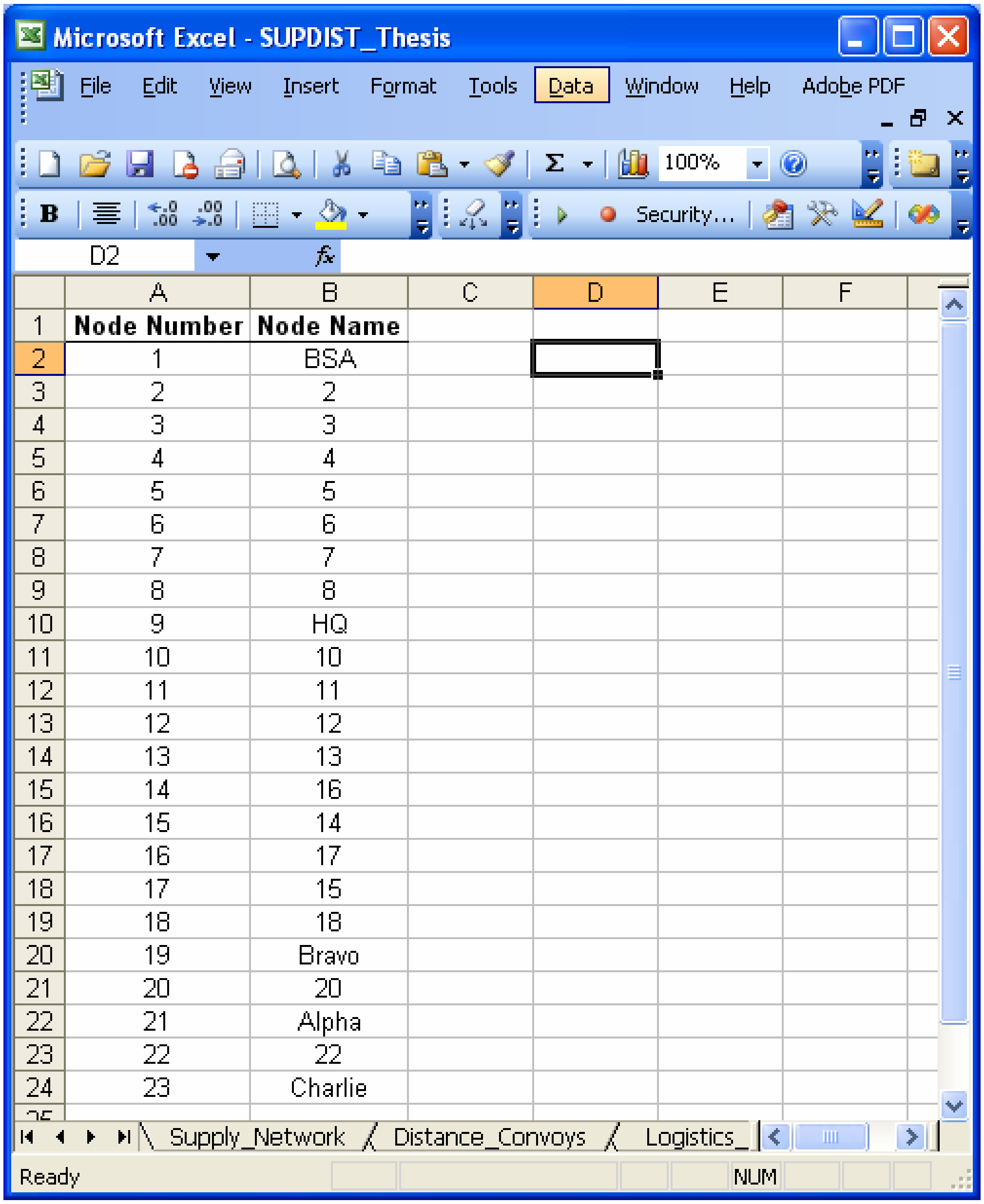


Figure 16. Notional supply distribution network.

2. Data Input for Scenario 2

The data requirements for Scenario 2 are shown below.



Node Number	Node Name
1	BSA
2	2
3	3
4	4
5	5
6	6
7	7
8	8
9	HQ
10	10
11	11
12	12
13	13
14	16
15	14
16	17
17	15
18	18
19	Bravo
20	20
21	Alpha
22	22
23	Charlie

Figure 17. Unit location and node assignments for Scenario 2.

This figure contains the data for the location of the units by node number. The spreadsheet displays the batteries location by node assignment and the logistics officer can plot the data to a map or overlay.

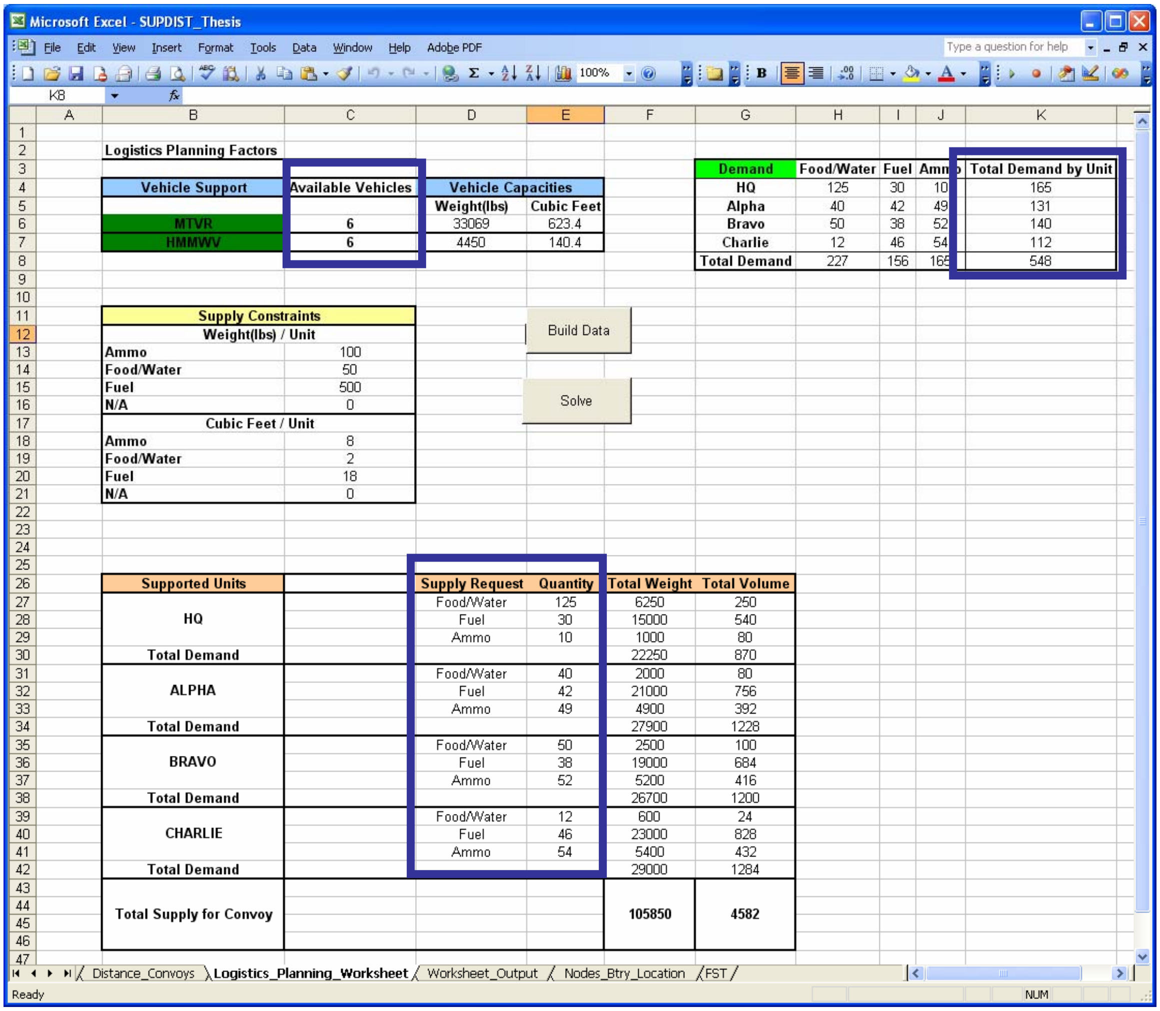


Figure 18. The type of vehicle and number of vehicles available for the convoy. This figure captures the class of supply and the amount requested by each unit.

The figure above displays the input data sent to GAMS to determine the optimal convoy for the second scenario. Since the scenario states the battalion must be prepared to move in order to provide fire support, the priority and quantity of demands shifts from Food/Water to more fuel and ammunition. The other difference in this scenario from the first scenario is that there is an extra HMMWV making the total number of vehicles available for the convoy 12 vice 11.

D. RESULTS TO SCENARIO 2

The results for the second scenario are listed below:

Scenario_2 - Notepad

File Edit Format View Help

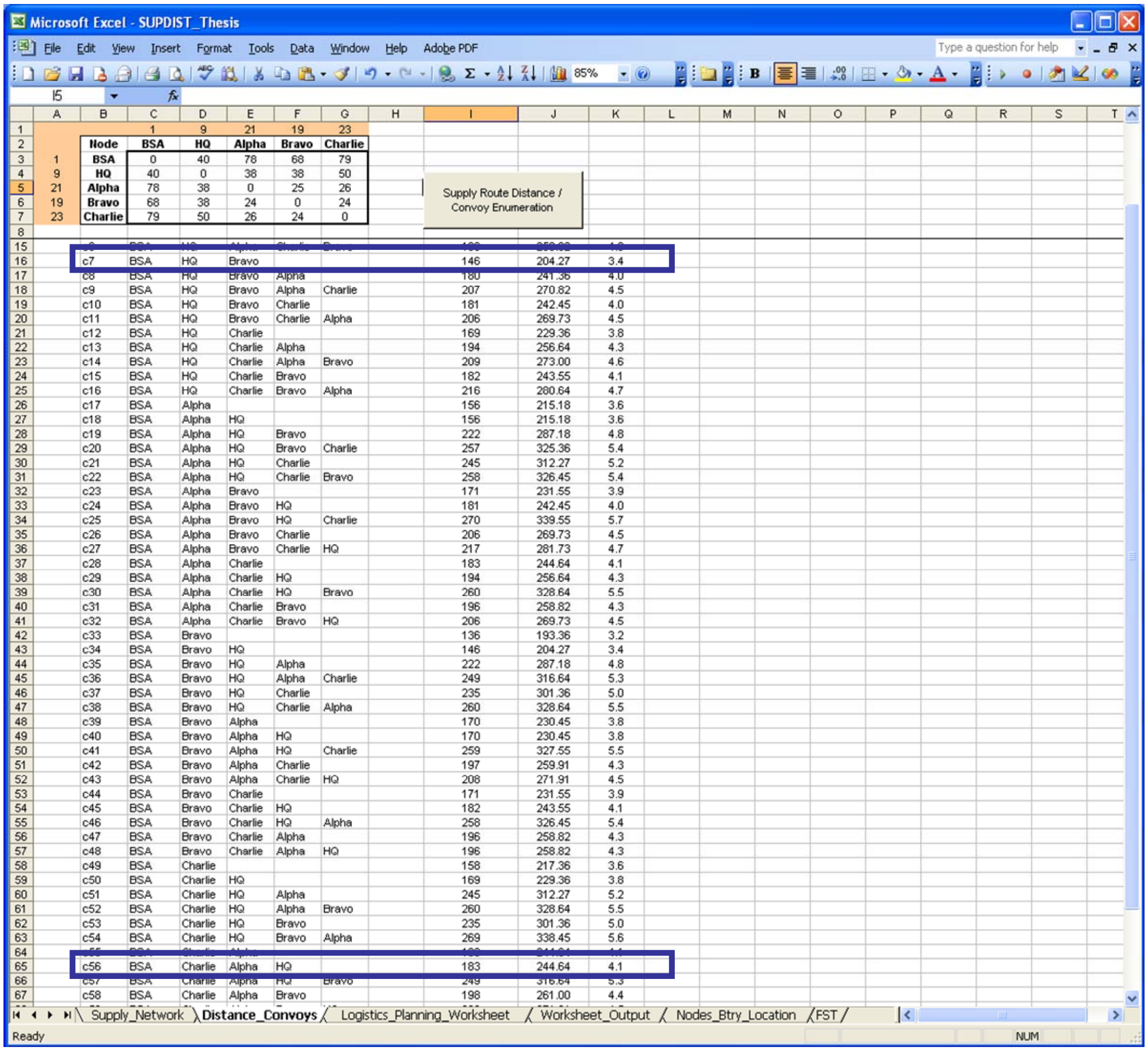
```
SUPDIST 1.00 24 AUG 2007

CONVOYS     WEIGHT    CUBIC FT
  c7        33388.9   1465.8
USES VEHICLES:     W_CAP      Q_CAP
      MTVR      33069.0    623.4
      HMMWV      4450.0    140.4
CARRIES:
        Ammo         :        52.0
        Food_Water   :       175.0
        Fuel         :        38.9
  c56       72483.3   3117.0
USES VEHICLES:     W_CAP      Q_CAP
      MTVR      33069.0    623.4
CARRIES:
        Ammo         :       113.0
        Food_Water   :        52.0
        Fuel         :       117.2

BATTERIES
  HQ
    RECEIVES       UNITS    NEEDS
    Ammo            10.0     10.0
    Food_Water     125.0    125.0
    Fuel            30.0     30.0
  Alpha
    RECEIVES       UNITS    NEEDS
    Ammo            49.0     49.0
    Food_Water      40.0     40.0
    Fuel            42.0     42.0
  Bravo
    RECEIVES       UNITS    NEEDS
    Ammo            52.0     52.0
    Food_Water      50.0     50.0
    Fuel            38.0     38.0
  Charlie
    RECEIVES       UNITS    NEEDS
    Ammo            54.0     54.0
    Food_Water      12.0     12.0
    Fuel            46.0     46.0
```

Figure 19. Results for Scenario 2.

Figure 19 lists the optimal supply route for the second scenario. Once again, the optimal solution is to use two convoys to distribute the supplies in an optimal manner. Here, the two convoys are c7 and c56.



Microsoft Excel - SUPDIST_Thesis

	Node	BSA	HQ	Alpha	Bravo	Charlie
		1	9	21	19	23
1	BSA	0	40	78	68	79
9	HQ	40	0	38	38	50
21	Alpha	78	38	0	25	26
19	Bravo	68	38	24	0	24
23	Charlie	79	50	26	24	0

Supply Route Distance / Convoy Enumeration

c6	BSA	HQ	Alpha	Charlie	Bravo	[illegible]	[illegible]	[illegible]
c7	BSA	HQ	Bravo			146	204.27	3.4
c8	BSA	HQ	Bravo	Alpha		180	241.36	4.0
c9	BSA	HQ	Bravo	Alpha	Charlie	207	270.82	4.5
c10	BSA	HQ	Bravo	Charlie		181	242.45	4.0
c11	BSA	HQ	Bravo	Charlie	Alpha	206	269.73	4.5
c12	BSA	HQ	Charlie			169	229.36	3.8
c13	BSA	HQ	Charlie	Alpha		194	256.64	4.3
c14	BSA	HQ	Charlie	Alpha	Bravo	209	273.00	4.6
c15	BSA	HQ	Charlie	Bravo		182	243.55	4.1
c16	BSA	HQ	Charlie	Bravo	Alpha	216	280.64	4.7
c17	BSA	Alpha				156	215.18	3.6
c18	BSA	Alpha	HQ			156	215.18	3.6
c19	BSA	Alpha	HQ	Bravo		222	287.18	4.8
c20	BSA	Alpha	HQ	Bravo	Charlie	257	325.36	5.4
c21	BSA	Alpha	HQ	Charlie		245	312.27	5.2
c22	BSA	Alpha	HQ	Charlie	Bravo	258	326.45	5.4
c23	BSA	Alpha	Bravo			171	231.55	3.9
c24	BSA	Alpha	Bravo	HQ		181	242.45	4.0
c25	BSA	Alpha	Bravo	HQ	Charlie	270	339.55	5.7
c26	BSA	Alpha	Bravo	Charlie		206	269.73	4.5
c27	BSA	Alpha	Bravo	Charlie	HQ	217	281.73	4.7
c28	BSA	Alpha	Charlie			183	244.64	4.1
c29	BSA	Alpha	Charlie	HQ		194	256.64	4.3
c30	BSA	Alpha	Charlie	HQ	Bravo	260	328.64	5.5
c31	BSA	Alpha	Charlie	Bravo		196	258.82	4.3
c32	BSA	Alpha	Charlie	Bravo	HQ	206	269.73	4.5
c33	BSA	Bravo				136	193.36	3.2
c34	BSA	Bravo	HQ			146	204.27	3.4
c35	BSA	Bravo	HQ	Alpha		222	287.18	4.8
c36	BSA	Bravo	HQ	Alpha	Charlie	249	316.64	5.3
c37	BSA	Bravo	HQ	Charlie		235	301.36	5.0
c38	BSA	Bravo	HQ	Charlie	Alpha	260	328.64	5.5
c39	BSA	Bravo	Alpha			170	230.45	3.8
c40	BSA	Bravo	Alpha	HQ		170	230.45	3.8
c41	BSA	Bravo	Alpha	HQ	Charlie	259	327.55	5.5
c42	BSA	Bravo	Alpha	Charlie		197	259.91	4.3
c43	BSA	Bravo	Alpha	Charlie	HQ	208	271.91	4.5
c44	BSA	Bravo	Charlie			171	231.55	3.9
c45	BSA	Bravo	Charlie	HQ		182	243.55	4.1
c46	BSA	Bravo	Charlie	HQ	Alpha	258	326.45	5.4
c47	BSA	Bravo	Charlie	Alpha		196	258.82	4.3
c48	BSA	Bravo	Charlie	Alpha	HQ	196	258.82	4.3
c49	BSA	Charlie				158	217.36	3.6
c50	BSA	Charlie	HQ			169	229.36	3.8
c51	BSA	Charlie	HQ	Alpha		245	312.27	5.2
c52	BSA	Charlie	HQ	Alpha	Bravo	260	328.64	5.5
c53	BSA	Charlie	HQ	Bravo		235	301.36	5.0
c54	BSA	Charlie	HQ	Bravo	Alpha	269	338.45	5.6
c55	BSA	Charlie	Alpha			[illegible]	[illegible]	[illegible]
c56	BSA	Charlie	Alpha	HQ		183	244.64	4.1
c57	BSA	Charlie	Alpha	HQ	Bravo	249	316.64	5.3
c58	BSA	Charlie	Alpha	Bravo		198	261.00	4.4

Supply_Network / Distance_Convoys / Logistics_Planning_Worksheet / Worksheet_Output / Nodes_Btry_Location / FST

Figure 20. Optimal convoy route, total convoy distance, and the total time to distribute supplies to all satisfy all demands and return to the BSA.

The optimal solution assigns one MTVR and all six HMMWV's to convoy c7, with the remaining five MTVR's assigned to c56. The distances for each convoy, respectively, are 146 miles and 183 miles. The total convoy vehicle miles is (7 * 146 + 5 * 183) = 1,937 total vehicle miles.

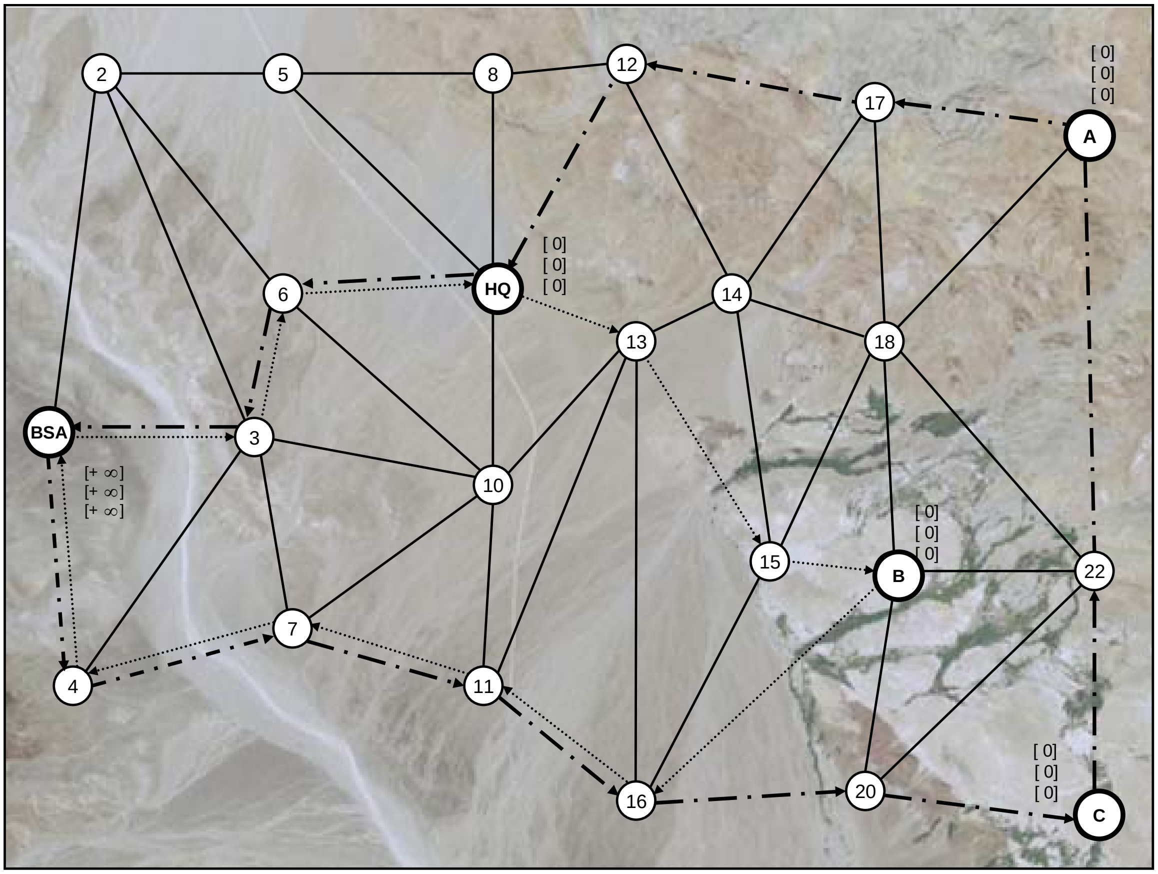
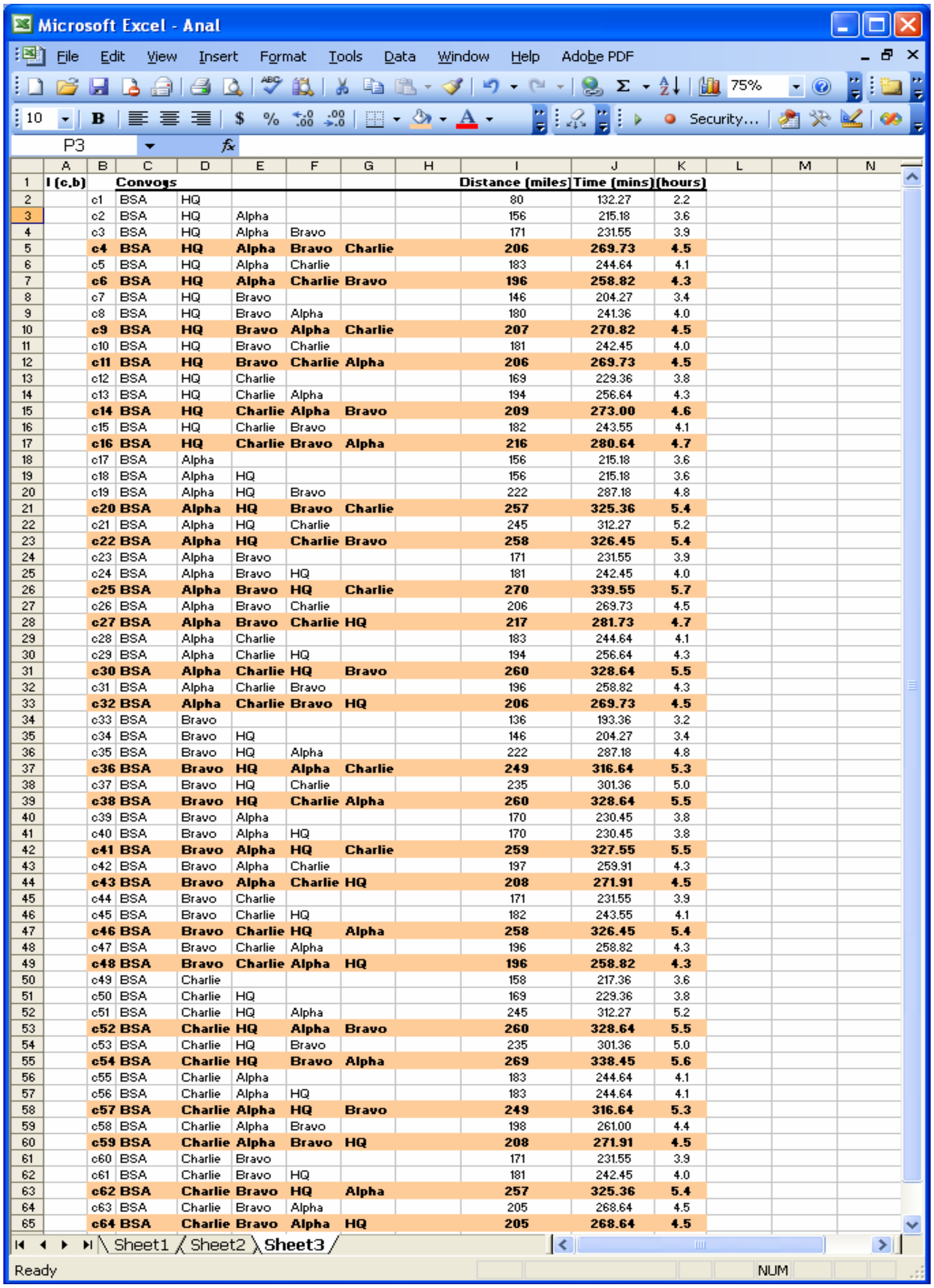


Figure 21. GAMS solution to Scenario 2. Convoy c7 is represented by the dotted lines. The convoy departs node 1 (BSA), travels to HQ located at node 9, travels to Bravo battery at node 19, then returns to the BSA at node 1. Convoy c56, depicted by the bold dashed line distributes supplies to Charlie battery at node 23, then to Alpha battery at node 21, and then delivers the remaining supplies to HQ battery at node 9 and returns to the BSA.

The decision support tool provides a solution that is significantly better than just using the Dijkstra distance table and estimating a convoy route. Suppose, for example, that the logistics officer uses all vehicles in one massive convoy that delivers supplies to every battery along the shortest path route. Figure 22 shows all potential convoys, and the highlighted ones are those that visit all demand points. This data does provide useful data to the logistics officer even if all he has to do is assign vehicles to a convoy and dispatch them on their route. From this table, one observes that convoy c6 (visiting HQ, Alpha, Charlie, and Bravo in order) has the shortest distance of 196 miles. By assigning all 12 vehicles to this convoy, the results are a total travel distance of 2,352 total vehicle

miles. The decision support tool reduces the “simple solution’ from the Dijkstra distance matrix and convoy enumeration by 17.6%. Another critical factor is time. With the “simple solution” from a single shortest-path convoy, the convoy does not return to the BSA for 4.3 hours. This means all 12 vehicles are gone and no vehicles are at the BSA to support any other supply requests and/or demands. With the optimal solution, convoy c7 will return in 3.4 hours giving the logistics officer seven vehicles to reassign to another convoy to support demands. Likewise, convoy c56 has a total convoy time of 4.1 hours until the five MTVR’s return to the BSA to be assigned their next convoy. The decision support tool is a valuable asset that allows flexible planning in asset allocation and convoy route selection that present optimal solutions.



I (c,b)	Convoys					Distance (miles)	Time (mins)	(hours)
c1	BSA	HQ				80	132.27	2.2
c2	BSA	HQ	Alpha			156	215.18	3.6
c3	BSA	HQ	Alpha	Bravo		171	231.55	3.9
c4	BSA	HQ	Alpha	Bravo	Charlie	206	269.73	4.5
c5	BSA	HQ	Alpha	Charlie		183	244.64	4.1
c6	BSA	HQ	Alpha	Charlie	Bravo	196	258.82	4.3
c7	BSA	HQ	Bravo			146	204.27	3.4
c8	BSA	HQ	Bravo	Alpha		180	241.36	4.0
c9	BSA	HQ	Bravo	Alpha	Charlie	207	270.82	4.5
c10	BSA	HQ	Bravo	Charlie		181	242.45	4.0
c11	BSA	HQ	Bravo	Charlie	Alpha	206	269.73	4.5
c12	BSA	HQ	Charlie			169	229.36	3.8
c13	BSA	HQ	Charlie	Alpha		194	256.64	4.3
c14	BSA	HQ	Charlie	Alpha	Bravo	209	273.00	4.6
c15	BSA	HQ	Charlie	Bravo		182	243.55	4.1
c16	BSA	HQ	Charlie	Bravo	Alpha	216	280.64	4.7
c17	BSA	Alpha				156	215.18	3.6
c18	BSA	Alpha	HQ			156	215.18	3.6
c19	BSA	Alpha	HQ	Bravo		222	287.18	4.8
c20	BSA	Alpha	HQ	Bravo	Charlie	257	325.36	5.4
c21	BSA	Alpha	HQ	Charlie		245	312.27	5.2
c22	BSA	Alpha	HQ	Charlie	Bravo	258	326.45	5.4
c23	BSA	Alpha	Bravo			171	231.55	3.9
c24	BSA	Alpha	Bravo	HQ		181	242.45	4.0
c25	BSA	Alpha	Bravo	HQ	Charlie	270	339.55	5.7
c26	BSA	Alpha	Bravo	Charlie		206	269.73	4.5
c27	BSA	Alpha	Bravo	Charlie	HQ	217	281.73	4.7
c28	BSA	Alpha	Charlie			183	244.64	4.1
c29	BSA	Alpha	Charlie	HQ		194	256.64	4.3
c30	BSA	Alpha	Charlie	HQ	Bravo	260	328.64	5.5
c31	BSA	Alpha	Charlie	Bravo		196	258.82	4.3
c32	BSA	Alpha	Charlie	Bravo	HQ	206	269.73	4.5
c33	BSA	Bravo				136	193.36	3.2
c34	BSA	Bravo	HQ			146	204.27	3.4
c35	BSA	Bravo	HQ	Alpha		222	287.18	4.8
c36	BSA	Bravo	HQ	Alpha	Charlie	249	316.64	5.3
c37	BSA	Bravo	HQ	Charlie		235	301.36	5.0
c38	BSA	Bravo	HQ	Charlie	Alpha	260	328.64	5.5
c39	BSA	Bravo	Alpha			170	230.45	3.8
c40	BSA	Bravo	Alpha	HQ		170	230.45	3.8
c41	BSA	Bravo	Alpha	HQ	Charlie	259	327.55	5.5
c42	BSA	Bravo	Alpha	Charlie		197	259.91	4.3
c43	BSA	Bravo	Alpha	Charlie	HQ	208	271.91	4.5
c44	BSA	Bravo	Charlie			171	231.55	3.9
c45	BSA	Bravo	Charlie	HQ		182	243.55	4.1
c46	BSA	Bravo	Charlie	HQ	Alpha	258	326.45	5.4
c47	BSA	Bravo	Charlie	Alpha		196	258.82	4.3
c48	BSA	Bravo	Charlie	Alpha	HQ	196	258.82	4.3
c49	BSA	Charlie				158	217.36	3.6
c50	BSA	Charlie	HQ			169	229.36	3.8
c51	BSA	Charlie	HQ	Alpha		245	312.27	5.2
c52	BSA	Charlie	HQ	Alpha	Bravo	260	328.64	5.5
c53	BSA	Charlie	HQ	Bravo		235	301.36	5.0
c54	BSA	Charlie	HQ	Bravo	Alpha	269	338.45	5.6
c55	BSA	Charlie	Alpha			183	244.64	4.1
c56	BSA	Charlie	Alpha	HQ		183	244.64	4.1
c57	BSA	Charlie	Alpha	HQ	Bravo	249	316.64	5.3
c58	BSA	Charlie	Alpha	Bravo		198	261.00	4.4
c59	BSA	Charlie	Alpha	Bravo	HQ	208	271.91	4.5
c60	BSA	Charlie	Bravo			171	231.55	3.9
c61	BSA	Charlie	Bravo	HQ		181	242.45	4.0
c62	BSA	Charlie	Bravo	HQ	Alpha	257	325.36	5.4
c63	BSA	Charlie	Bravo	Alpha		205	268.64	4.5
c64	BSA	Charlie	Bravo	Alpha	HQ	205	268.64	4.5

Figure 22. Convoy Enumeration for Scenario 2. The highlighted convoys indicate convoys that visit every battery.

This data does provide useful data to the logistics officer even if all he has to do is assign vehicles to a convoy and dispatch them on their route.

Figure 23 contains the GAMS convoy solution and compares it to the shortest, longest, and average Dijkstra's distance solution. As we see, even with the Dijkstra's shortest convoy route, the GAMS solution reduces it by 17.6% or 415 total vehicle miles. Likewise, for the for longest convoy route from Dijkstra's distance matrix, the reduction is significantly higher at 40.2% or 1,303 total vehicle miles.

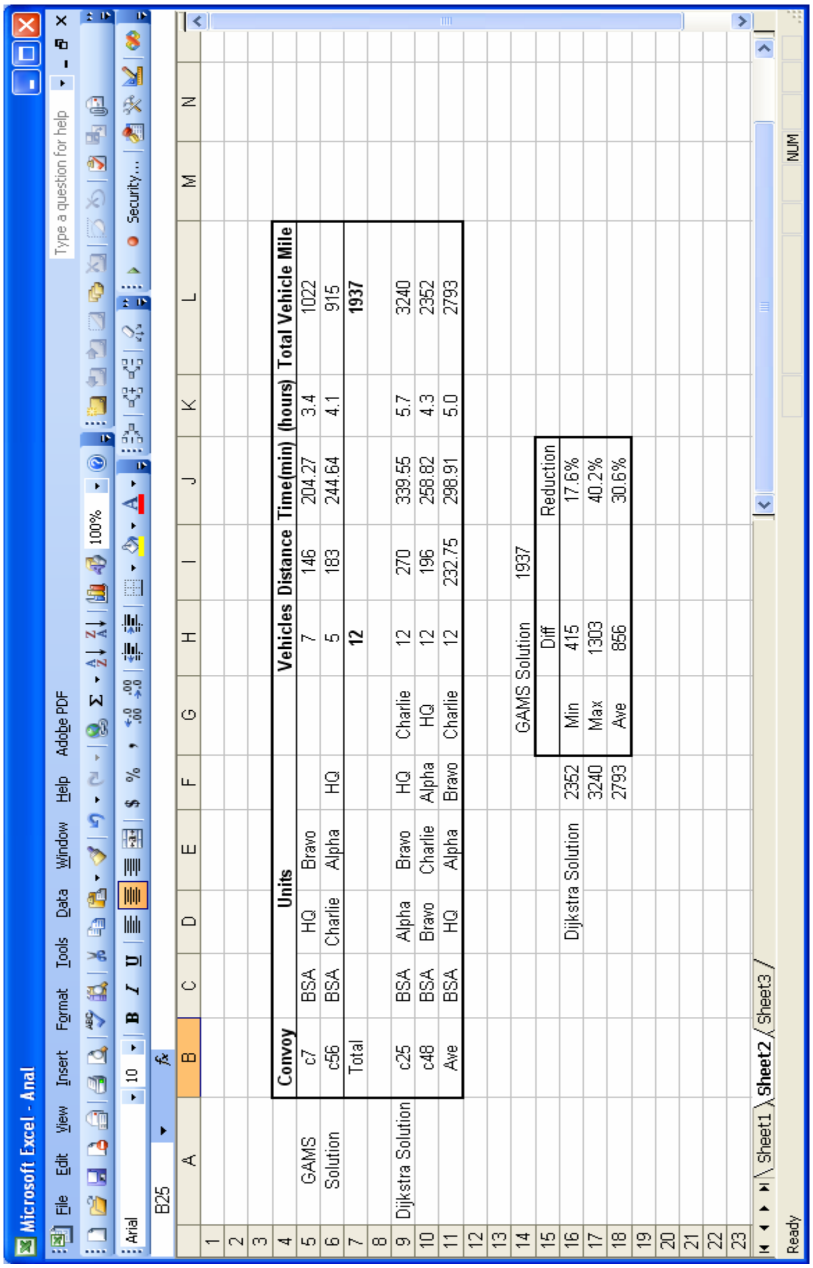


Figure 23. GAMS solution compared to Dijkstra's algorithm solution.

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V. CONCLUSION

A. SUMMARY

1. Summary of the Problem

This thesis addresses the problem of determining a supply distribution route in support of sustainment operations to forward deployed units. The model, identified in Chapter III and implemented in Chapter IV, not only finds an optimal solution, the spreadsheets make it easy for the logistics officer to use it in practice.

2. Model Assumptions

The model solves the supply distribution problem while making several assumptions:

- It assumes that any vehicle available for the convoy is in perfect working condition and will not breakdown while part of the convoy.
- It assumes that vehicles can travel at 60 miles per hour, while each delivery consumes only 45 minutes of time.
- It assumes all roads are easily traveled and are not restrictive, meaning all vehicles and vehicle loads are capable of traversing any road in any direction.
- Moreover, the model leverages the following simplifications:
    - Only three classes of supply
    - It assumed notional data regarding size and weight.
- Convoys are assigned for a single time period, and one time period is treated independently of the next to fulfill all demand requests.

The deterministic nature of the first three assumptions is unrealistic. Vehicles can and do breakdown before, during, or after their assigned convoy and their travel speeds are not exact. Also, requests for logistical support or supplies come in at random times where a critical item(s) is urgently needed to continue the mission. These added elements create planning challenges for the logistics officer on how and when to distribute supply support. This model also assumes all vehicles are deployed to convoys, when more than

likely the logistics officer may have access to more vehicles or be able to acquire a vehicle within the battalion to deliver the urgent request. The last critical assumption is that the only supply support that is requested are the three classes (Class I Food/Water, Class III Fuel, and Class V Ammunition).

3. Summary of the Results

Our model is built on a set of fixed assumptions mentioned above. Even though many of the assumptions are not entirely realistic, the results that the model provides are extremely helpful to the decision maker.

From Scenario 1, the visual inspection of the convoy route that satisfies all demands was c4 totaling 142 miles to complete the convoy which equals 1,562 total vehicle miles. The model, using the exact same assumptions and data input, calculates two convoys, c18 and c64. The respective distances for each are 50 miles and 142 miles. As one observes, convoy c64 has the same distance as the solution obtained by visual inspection. However, the model broke the convoy into two and divided the vehicles and supplies that would satisfy demands at all battery locations. When compared to a single convoy of 11 vehicles traveling a total of 142 miles each, the optimal solution is to send two convoys of seven and four, respectively. The result is a savings of 644 vehicle-miles, which is about 42% of the total vehicle-miles traveled.

Similarly, if we compare results in Scenario 2 we see an even greater reduction in total vehicle miles per convoy. In this scenario the logistics officer has 12 vehicles available for assignment to a convoy. From the table in Figure 22, possible convoy distances range from 196 miles (the lower bound) and 270 miles (the upper bound). The total vehicle distance for the 12 vehicles travel are 2,352 miles and 3,240 miles and requires 4.3 hours and 5.7 hours to complete, respectively. As we saw from the results to Scenario 2, the model proves itself a useful tool by minimizing the total vehicle mileage for the convoy while still satisfying all the demands. The model found that convoy c7 with five vehicles and convoy c56 with seven vehicles was the optimal distribution plan

and convoy route. The total vehicle mileage is 1,937 miles for the two convoys and will take no longer than 4.2 hours (the total time to complete convoy c56 which is the longer convoy).

The other capability this model and decision tool provides is basic sensitivity analysis. For example, it is trivial to rerun our model either with one additional or one fewer vehicle to determine if this change would impact our ability to support the forward-deployed units as well as the optimal convoys for doing so. The information from the analysis could provide insightful information to the commander in his planning process.

B. FUTURE RESEARCH

Despite the assumptions, our model produces helpful results to the logistics officer and/or decision maker. This model takes a first step in planning convoy routes to distribute supplies in an optimal manner. In order to make this model stronger, assumptions can and should be relaxed. Examples include:

- Better description of road surfaces and restrictions;
- Realistic and varying speeds of the convoy(s);
- Loading and Offloading times of supplies on the vehicles;
- Vehicle breakdowns while dispatched on the convoy;
- Explicit priorities of need for units as well for the classes of supply;
- Automatic handling of infeasibility via commodity priorities and penalty functions
- Additional classes of supply (to include actual packaging data, i.e., weight, size, and unit);
- Fuel consumption of the vehicles on the convoy;
- Use of empty vehicles for other logistical services and functions;
- Road interdictions and re-routing of the convoy after the convoy has already departed the BSA; and
- Apply or adjust alternative objective functions:
    - Minimize the total vehicle-miles
    - Complete the supply distribution in the shortest amount of time

This model provides the foundation for additional research to build a stronger and more adaptable decision support tool to assist further the logistics officer in planning supply distribution convoys in a rapidly changing environment.

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